NERRS Science Collaborative Project:
Assessing how climate change will affect coastal habitats in the Northeast
Available: August 2017

NORTHEAST REGIONAL RESOURCE DOCUMENT

SALT MARSH HABITAT

The following includes excerpted text from the many reference documents reviewed by both project team members and partner agency participants in preparation for assessing the vulnerability of salt marsh habitat in the Northeast. It is intended to provide an overview of the 'state of knowledge' regarding the impact of climate change on this habitat and serve as a general resource for other organizations that wish to perform similar vulnerability assessments within the region.

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DIRECT EFFECTS

Direct Effects

CURRENT CONDITION

…the decline in forb panne cover in control plots in Rhode Island over the experimental period (Figs 1 and 2c) indicates that climate effects are already reducing panne habitat area and species diversity in southern New England marshes.

Gedan KB and MD Bertness. 2009. Experimental warming causes rapid loss of plant diversity in New England salt marshes. Ecology Letters 12:842-848. Doi: 10.111/j.1461-0248.2009.01337.x

Analyses of aerial photographs dating back to 1947 reveals that extensive marsh area loss and alterations in tidal creek structure have occurred where vegetation along the edges of tidal creeks and mosquito ditches in the low marsh has declined or disappeared. Where edge vegetation has not been lost, and where major changes in tidal inlet size have not resulted in flows that cause erosion and bank slumping, marsh area and creek structure has remained very stable.

Smith SM. 2009. Multi-decadal changes in salt marshes of Cape Cod, MA: Photographic analyses of vegetation loss, species shifts, and geomorphic change. Northeastern Naturalist 16(2):183-208.

Five main patterns of change are evident in salt marshes across Cape Cod. They are: i) tidal creek widening, creek structural changes, and marsh area reductions associated with edge vegetation losses; ii) tidal creek widening and creek structural changes associated with increases in the width of tidal inlets; iii) marsh edge/area stability; iv) high-marsh losses (landward retreat) with replacement by un-vegetated mudflats; and v) high-marsh losses balanced by low-marsh encroachment.

Smith SM. 2009. Multi-decadal changes in salt marshes of Cape Cod, MA: Photographic analyses of vegetation loss, species shifts, and geomorphic change. Northeastern Naturalist 16(2):183-208.

The majority of marshes on Cape Cod have exhibited variable reductions in high-marsh area, but without the development of unvegetated mudflat during the process. In fact, there have been some very rapid shifts in vegetation that demonstrate the ability of *S. alterniflora* to keep pace with retreating S. patens.

Smith SM. 2009. Multi-decadal changes in salt marshes of Cape Cod, MA: Photographic analyses of vegetation loss, species shifts, and geomorphic change. Northeastern Naturalist 16(2):183-208.

In Pleasant Bay, large areas of high marsh converted to low marsh between 1984 and 2000. This area has been greatly affected by alterations in tidal amplitude caused by barrier-beach migration and breaks. As mentioned previously, a 1987 storm produced a new inlet that greatly increased tidal amplitude. Subsequently, the majority of high marsh that proliferated between 1947 and 1984 (due to decreasing tidal amplitude from southward migration of the tidal inlet and the establishment of additional mosquito ditches) virtually disappeared. In some places, the low/high marsh boundary shifted landward by as much as 650 m between 1984 and 2000 (Fig. 6).

Smith SM. 2009. Multi-decadal changes in salt marshes of Cape Cod, MA: Photographic analyses of vegetation loss, species shifts, and geomorphic change. Northeastern Naturalist 16(2):183-208.

With respect to the timeline of vegetation losses, color IR photography shows that both low and high-marsh vegetation losses on Cape Cod have been occurring since at least 1984, and possibly for several decades….The photography also shows that vegetation losses have not occurred simultaneously; they began at different times for different marshes. This temporal staggering suggests that no single climatic event (e.g., extreme drought) forced the disappearance of vegetation all at once, either independently or in conjunction with consumer pressure and/or pathogens, as is reportedly the case with SWD in Georgia (Ogburn and Alber 2006, Silliman et al. 2005) and Louisiana (McKee et al. 2004).

Smith SM. 2009. Multi-decadal changes in salt marshes of Cape Cod, MA: Photographic analyses of vegetation loss, species shifts, and geomorphic change. Northeastern Naturalist 16(2):183-208.

Marsh ecosystems are variable, both spatially and temporally. Factors such as proximity to major tidal channels and inlets, as well as the character of peat substrate, are important to defining spatial variation. Storms are clearly important in delivering pulses of sediment to the marsh surface and these vary in time and space.

Roman CT, Peck JA, Allen JR, King JW and PG Appleby. 1997. Accretion of a New England (U.S.A.) salt marsh in response to inlet migration, storms, and sea-level rise. Estuarine, Coastal and Shelf Science 45: 717-727.

We developed and implemented a rapid assessment method to quantify salt marsh degradation related to SLR and to help predict the vulnerability of individual marshes to imminent SLR. The method uses vegetation community distribution and composition, soil bearing capacity, elevation, and predictions of marsh loss under SLR scenarios as indicators of salt marsh vulnerability to SLR. Given the limited resources available for intervention and adaptation, a RAM to assess vulnerability to SLR can be used in combination with other data sources (e.g., conservation value; indices of biological integrity, etc.) to help prioritize sites for intervention.

Cole Eckberg ML, Watson EB, Raposa KB, Ferguson WS and K Ruddock. 2017. Development and application of a method to identify salt marsh vulnerability to sea level rise. Estuaries and Coasts. 40(3): 117-141.

Storm surges push salt water up estuarine gradients, raising salinities in brackish and freshwater tidal marshes and temporarily shifting plant distributions. Floodwaters can drown salt marsh mammals and ground-nesting birds, causing brief and localized population declines (Michener et al. 1997).Increases in storm intensity will likely increase interannual and intermarsh variability in sedimentation rates.

Gedan KB, Silliman BR and MD Bertness. 2009. Centuries of human-driven change in salt marsh ecosystems. Annual Review of Marine Science 1: 117-141.

Although mineral sedimentation may be affected by vegetation characteristics, biotic processes that contribute directly to soil volume have the greatest potential to influence vertical accretion and elevation change. These biological processes can be divided into surface and subsurface processes. Surface processes include the accumulation of decaying organic matter such as leaf litter, or the formation of living benthic mats (e.g., microbial, algal, root), which contribute to vertical accretion and also influence the resistance of the deposit to compaction or erosion. Subsurface processes such as root production, root mortality, and decomposition influence soil volume, contributing either to expansion or to subsidence.

Cahoon DR, Hensel PF, Spencer T, Reed DJ , McKee KL and N Saintilan. 2006. Coastal wetland vulnerability to relative sea-level rise: Wetland elevation trends and process controls. Ecological Studies Vol.190 J.T.A.Verhoeven, B.Beltman, R.Bobbink, and D.F.Whigham (Eds.) Wetlands and Natural Resource Management © Springer-Verlag Berlin Heidelberg

Accumulation of soil organic matter occurs when production exceeds decomposition rates. In coastal wetlands, slow decomposition, particularly of plant roots, occurs under the predominately anaerobic conditions in flooded soils. Thus, variation in root production may be the primary influence on elevation change through root inputs to soil volume. For example, reductions in soil organic matter accumulation following mass plant mortality (i.e., lack of root input) can lead to elevation declines through peat collapse (Cahoon et al. 2003, 2004).

Cahoon DR, Hensel PF, Spencer T, Reed DJ, McKee KL and N Saintilan. 2006. Coastal wetland vulnerability to relative sea-level rise: Wetland elevation trends and process controls. Ecological Studies Vol.190 J.T.A.Verhoeven, B.Beltman, R.Bobbink, and D.F.Whigham (Eds.) Wetlands and Natural Resource Management © Springer-Verlag Berlin Heidelberg

Whereas 'mature' marsh surfaces will exhibit an equilibrium level related to tidal parameters and thus respond to changes in sea level and frequency of tidal inundation, 'immature' marshes will show high, non-equilibrium rates of accretion and surface change as they build up rapidly from low positions in the tidal frame.

Cahoon DR, Hensel PF, Spencer T, Reed DJ, McKee KL and N Saintilan. 2006. Coastal wetland vulnerability to relative sea-level rise: Wetland elevation trends and process controls. Ecological Studies Vol.190 J.T.A.Verhoeven, B.Beltman, R.Bobbink, and D.F.Whigham (Eds.) Wetlands and Natural Resource Management © Springer-Verlag Berlin Heidelberg

Northeastern US salt marshes face multiple co-stressors, including accelerating rates of relative sea level rise (RSLR), elevated nutrients inputs, and low sediment supplies. In order to evaluate how marsh surface elevations respond to such factors, we used surface elevation tables (SETs) and surface elevation pins to measure changes in marsh surface elevation in two eastern Long Island Sound salt marshes, Barn Island and Mamacoke Marsh. We compare marsh elevation change at these two systems with recent rates of RSLR and find evidence of differences between the two sites; Barn Island is maintaining its historic rate of elevation gain (2.3 ± 0.24 mm yr-1 from 2003 to 2013) and is no longer keeping pace with RSLR, while Mamacoke shows evidence of a recent increase in rates (4.2 ± 0.52 mm yr-1 from 1994 to 2014) to maintain its elevation relative to sea level. In addition to data on short-term elevation responses at these marshes, both sites have unusually long and detailed data on historic vegetation species composition extending back more than half a century. Over this study period, vegetation patterns track elevation change relative to sea levels, with the Barn Island plant community shifting towards those plants that are found at lower elevations and the Mamacoke vegetation patterns showing little change in plant composition. We hypothesize that the apparent contrasting trend in marsh elevation at the sites is due to differences in sediment availability, salinity, and elevation capital. Together these two systems provide critical insight into the relationships between marsh elevation, high marsh plant community, and changing hydroperiods. Our results highlight that not all marshes in southern New England may be responding to accelerated rates of RSLR in the same manner.

Carey JC, Raposa KB, Wigand C and SW Warren. 2017. Contrasting decadal-scale changes in elevation and vegetation in two Long Island Sound salt marshes. Estuaries and Coasts. 40(3):651-661.

Studies of the Wequetequock-Pawcatuck tidal marshes over four decades have documented dramatic changes in vegetation that appear to be related primarily to differential rates of marsh accretion and sea-level rise. Other environmental factors such as sediment supply and anthropogenic modifications of the system may be involved as well. When initially studied in 1947-1948 the high marsh supported a *Juncus gerardii-Spartina patens* belting pattern typical of many New England salt marshes. On most of the marsh complex the former *Juncus* belt has been replaced by forbs, primarily *Triglochin maritima*, while the former *S. patens* high marsh is now a complex of vegetation types – stunted *Spartina alterniflora, Distichlis spicata*, forbs, and relic stands of *S. patens*….Marsh elevations were determined by leveling, and the mean surface elevation of areas where the vegetation has changed is significantly lower than that of areas still supporting the earlier pattern (4.6 vs. 13.9 cm above mean tide level). The differences in surface elevation reflect differences in accretion of marsh peat.

Warren RS and WA Niering. 1993. Vegetation change on a northeast tidal marsh: interaction of sea-level rise and marsh accretion. Ecology 74(1):96-103.

A multi-decadal analysis of salt marsh aerial extent using historic imagery and maps revealed that salt marsh vegetation loss is both widespread and accelerating, with vegetation loss rates over the past four decades summing to 17.3 %.

Watson EB, Wigand C, Davey EW, Andrews HM, Bishop J and KB Raposa. 2016. Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for Southern New England. Estuaries and Coasts DOI 10.1007/s12237-016-0069-1

Marsh geomorphic setting appears to exert a strong control on multi-decadal changes in vegetated marsh area at focus sites. For the backbarrier marshes profiled (Nag Marsh and Mary Donovan Marsh), the extent of marsh vegetation expanded from 1939 through 1985 and contracted from 1985 to 2011 (Fig. 7). For fringing marshes, however, vegetation loss appears gradual and approximately linear. Extending this analysis to historic US Coast Survey maps dating to the 1860s (Fig. 7, Table 2) shows that declines in wetland vegetation have been occurring since the 1860s.

Watson EB, Wigand C, Davey EW, Andrews HM, Bishop J and KB Raposa. 2016. Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for Southern New England. Estuaries and Coasts DOI 10.1007/s12237-016-0069-1

Loss of vegetation has occurred through multiple mechanisms, including shoreline erosion, loss of marsh in the bay head region of backbarrier lagoons and estuaries, and widening and headward erosion of tidal channels. In addition, marshes have seen the formation and expansion of interior ponds in areas of poor drainage, behind blocked ditches, and in the center point of grid-ditched marsh islands.

Watson EB, Wigand C, Davey EW, Andrews HM, Bishop J and KB Raposa. 2016. Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for Southern New England. Estuaries and Coasts DOI 10.1007/s12237-016-0069-1

Conceivably, a number of processes are interacting synergistically to produce the observed channel extension, the key being the topographic depression of creek heads, which precedes channel progression onto the marsh platform. Possible contributing factors include physical removal of sediment by crab burrowing, collapse of sediments due to crab burrowing, destabilization of sediments due to the removal of vegetation and rooting, and increased decomposition of organic matter due to infiltration of oxygenated water in burrowed regions. These processes have been reported in other wetland studies [May, 2002; Paramor and Hughes, 2004].

Hughes ZJ, FitzGerald DM, Wilson CA, Pennings SC, Więski K and A Mahadevan. 2009. Rapid headward erosion of marsh creeks in response to relative sea level rise, Geophys. Res. Lett., 36, L03602, doi:10.1029/2008GL036000.

DIRECT EFFECTS

INCREASE IN CO_2

…, field observations from an organic-rich Chesapeake Bay salt marsh indicate that elevated atmospheric CO_2 concentrations may make it possible for coastal marshes to keep pace with RSLR through increases in fine root productivity, especially at lower salinities (Langley et al. 2009). However, when sediment supplies are low or when the pace of RSLR is rapid, marshes may not be able to keep pace with RSLR (Morris et al. 2005; Nelson and Zavaleta 2012).

Carey JC, Moran SB, Kelly RP, Kolker AS and RW Fulweiler. 2017. The declining role of organic matter in New England salt marshes. Estuaries and Coasts. 40(3): 626-639.

The authors used a mesocosm experiment to test the effect of elevated CO2 (720 ppm) on the ability of marsh vegetation (a mix of *Spartina patens* and *Schoenoplectus americanus* from a NWR in Louisiana) to tolerate salinity and flooding increases associated with sea level rise. Salinity levels tested were 0, 5, 10, 15, and 20 ppt sea salts, and flooding regimes included drained, intermittently flooded, and flooded. Findings indicated that elevated CO2 allowed *S. americanus* (a C3 species) to withstand salinity, and increased biomass (and elevation) by promoting shoot-base expansion.

Cherry JA, McKee KL and JB Grace. 2009. Elevated CO2 enhances biological contributions to elevation change in coastal wetlands by offsetting stressors associated with sea-level rise. Journal of Ecology 97(1): 67-77.

This field investigation was carried out in a Chesapeake Bay marsh dominated by *Spartina patens*, *Distichlis spicata*, and *Schoenoplectus americanus*. In a factorial design, the authors tested the effects of 2 CO2 levels (ambient and > 700 ppm) and 2 nitrogen enrichment levels (0 and 25 g ammonium-N m-2 yr-1). Plots had SET tables to measure elevation change. Findings demonstrate that elevated CO2 accelerated soil elevation gain over the course of the 2 year study through stimulation of belowground biomass productivity.

Langley JA, McKee KL, Cahoon DR, Cherry JA and JP Megonigal. 2009. Elevated CO2 stimulates marsh elevation gain, counterbalancing sea-level rise. Proceedings of the National Academy of Sciences. 106(15): 6182-6186.

Climate-related changes to the carbon cycle are likely to alter the sequestration service provided by salt marshes, as well as affect long-term rates of salt marsh accretion and the ability of marshes to keep pace with sea level rise in ways that are still unclear. Evidence suggests that the response of salt marshes to elevated CO2 will be dependent on plant composition and that higher concentrations of CO2 will favor compositional shifts toward C3 plants, as C4 plants are gradually outproduced and outcompeted.

Gedan KB, Silliman BR and MD Bertness. 2009. Centuries of human-driven change in salt marsh ecosystems. Annual Review of Marine Science 1: 117-141.

…, plants with the C3 photosynthetic pathway typically respond more to increases in CO_2 concentration than do plants with the C4 photosynthetic pathway (Acock and Allen 1985). This differential sensitivity can lead to changes in competitive ability (Zangerl and Bazzaz 1984) and potentially to changes in community composition (Bazzaz et al. 1985).

Curtis PS, Drake BG and DF Whigham. 1989. Nitrogen and carbon dynamics in C3 and C4 estuarine marsh plants grown under elevated CO2 in situ. Oecologia 78(3): 297-301.

Elevated CO_2 ameliorated negative effects of salinity stress and enhanced production compared to ambient CO_2 conditions, especially for the C3 species, *S. americanus*. Although *S. americanus* had a greater effect on elevation change, the presence of the C4 species, *S. patens* negatively affected *S. americanus* production and may limit the ability of *S. americanus* to contribute to positive elevation change. If increased CO_2 ameliorates the effects of salinity stress in coastal marshes, thus increasing resilience of some species, then those species may achieve a greater competitive advantage over other species less responsive to changes in CO_2. The greater contribution of *S. americanus* to elevation suggests that future shifts in composition of wetland plant communities could influence the capacity of marshes to maintain surface elevations relative to sea-level.

Cherry JA, McKee KL and JB Grace. 2009. Elevated CO2 enhances biological contributions to elevation change in coastal wetlands by offsetting stressors associated with sea-level rise. Journal of Ecology 97(1): 67-77.

This study examined the metabolic responses of a high salt marsh to increased inundation and wrack deposition associated with sea level rise. We measured changes in ecosystem and soil photosynthesis and respiration by analyzing carbon dioxide fluxes in the light and dark. Data from seasonal flux measurements were combined with continuously measured light and temperature data to develop a model that estimated annual production and respiration. Results suggested that increased inundation will reduce respiration rates to a greater extent than production, yielding a moderate net loss of organic carbon from the high marsh. The model also predicted a substantial loss of organic carbon from wrack-affected areas. This decreased organic carbon input may play an important role in the ability of the marsh to maintain elevation relative to sea level rise.

Miller WD, Neubauer SC and IC Anderson. 2001. Effects of sea level induced disturbances on high salt marsh metabolism. Estuaries. 24(3): 357-367.

INCREASE IN TEMPERATURE

Based on the fact that summer (July, August, September) annual average water temperatures were 20.3 ºC from 1960 to 1969 and 22.3 ºC from 2000 to 2011, we used the relationship given by Valiela et al. (1985) to calculate a 9.4±1.4% increase in low marsh decomposition rates since 1960 due to increased surface water temperatures in the estuary. Considering the important role of organic matter in maintaining the elevation of these sediments, a nearly 10% increase in decomposition rates could be enough to tip the balance of accretion processes towards marsh submergence.

Carey JC, Moran SB, Kelly RP, Kolker AS and RW Fulweiler. 2017. The declining role of organic matter in New England salt marshes. Estuaries and Coasts. 40(3): 626-639.

Warming favoured *Spartina patens* growth over forb panne species, which were subsequently reduced in cover or lost from warmed plots. By affecting the distribution of the *S. patens* zone, warming reduced plant diversity by 74% at Little River Marsh and 44% at Nag Creek in just three growing seasons (Fig 3a).

Gedan KB and MD Bertness. 2009. Experimental warming causes rapid loss of plant diversity in New England salt marshes. Ecology Letters 12:842-848. Doi: 10.111/j.1461-0248.2009.01337.x

In the case of *S. patens*-dominated New England salt marshes, however, our results suggest that global temperature increase, predicted to alter biogeochemical cycles and species composition in many ecosystems (e.g., Klein et al. 2004; Oberbauer et al. 2007; Walker et al. 2006; Zavaleta et al. 2003), may not have as large an effect as other disturbances.

Gedan KB and MD Bertness. 2010. How will warming affect the salt marsh foundation species Spartina patens and its ecological role? Oecologia 164:479-487. DOI 10.1007/s00442-010-1661-x

…our analysis provides a first-order approximation of how increase in estuarine water temperatures over the last several decades may have fueled decomposition rates in such a way that organic matter now contributes less to marsh accretion compared to historical records. The fact that the contribution from organic matter has declined in all our cores compared to historical values supports this hypothesis, as changes in water temperature have likely impacted the entire estuary (Fulweiler et al. 2015).

Carey JC, Raposa KB, Wigand C and SW Warren. 2017. Contrasting decadal-scale changes in elevation and vegetation in two Long Island Sound salt marshes. Estuaries and Coasts. 40(3):651-661.

Marshes worldwide are actively degrading in response to increased sea level rise rates and reduced sediment delivery, though the growth rate of vegetation plays a critical role in determining their stability. We have compiled 56 measurements of aboveground annual productivity for *Spartina alterniflora*, the dominant macrophyte in North American coastal wetlands. Our compilation indicates a significant latitudinal gradient in productivity, which we interpret to be determined primarily by temperature and/or the length of growing season.

Kirwan ML, Guntenspergen GR and JT Morris. 2009. Latitudinal trends in Spartina alterniflora productivity and the response of coastal marshes to global change. Global Change Biology 15(8):1982–1989.

CHANGE IN PRECIPITATION

As climate change progresses, estuarine salinities (and soil salinities in adjacent tidal marshes) will be affected by shifts in three primary factors: (1) total regional precipitation, (2) seasonal timing of precipitation and runoff patterns (in particular shifts in the amount of snow vs. rainfall and shifts in snowmelt periods), and (3) increases in sea level.

Callaway JC, Parker VT, Vasey MC and LM Schile. 2007. Emerging issues for the restoration of tidal marsh ecosystems in the context of predicted climate change. Madrono. 54(3): 234-248

Increases in rainfall associated with global climate change may slow coastal forest retreat in the face of sea-level rise, while the increased incidence of droughts or consumptive water use by humans may accelerate it.

Williams K, Ewel KC, Stumpf RP, Putz FE and TW Workman. 1999. Sea-level rise and coastal forest retreat on the west coast of Florida, USA. Ecology. 80(6): 245-263. doi: 10.1890/0012-9658(1999)080[2045:SLRACF]2.0.CO;2

Longer-term trends (e.g., weekly to seasonal) in groundwater levels can influence wetland surface elevation….. , lowering of the marsh water table by drought resulted in a decrease in surface elevation in marshes in east Texas (10–15 mm; Perez and Cahoon 2004), in south Louisiana (20 mm; Perez et al. 2003; Swarzenski et al. 2006; Fig. 12.4), and in southeast Australia (Rogers et al. 2005).

Cahoon DR, Hensel PF, Spencer T, Reed DJ , McKee KL and N Saintilan. 2006. Coastal wetland vulnerability to relative sea-level rise: Wetland elevation trends and process controls. Ecological Studies Vol.190 J.T.A.Verhoeven, B.Beltman, R.Bobbink,and D.F.Whigham (Eds.) Wetlands and Natural Resource Management © Springer-Verlag Berlin Heidelberg

As climate change progresses, estuarine salinities (and soil salinities in adjacent tidal marshes) will be affected by shifts in three primary factors: (1) total regional precipitation, (2) seasonal timing of precipitation and runoff patterns (in particular shifts in the amount of snow vs. rainfall and shifts in snowmelt periods), and (3) increases in sea level.

Callaway JC, Parker VT, Vasey MC and LM Schile. 2007. Emerging issues for the restoration of tidal marsh ecosystems in the context of predicted climate change. Madrono. 54(3): 234-248

…, at current and elevated $p\mathrm{CO}_2$, the C4 species showed relatively greater recovery of leaf area and biomass production compared to the C3 species, suggesting that the C4 species would continue to be more competitive than the C3 species in regions receiving more frequent and severe drought in the future.

Ward JK, Tissue DT, Thomas RB and BR Strain. 1999. Comparative responses of model C3 and C4 plants to drought in low and elevated CO2. Global Change Biology. 5: 857–867. doi:10.1046/j.1365-2486.1999.00270.x

In contrast to inundation, reduced precipitation and drought were not found to have significant impacts on *S. patens* growth and there was no significant interaction found between precipitation and any of the inundation treatments.

Watson EB, Szura K, Wigand C, Raposa KB, Blount K and M Cencer. 2016. Sea level rise, drought and the decline of Spartina patens in New England marshes. Biological Conservation 196:173-181.

CHANGE IN SEA LEVEL

Recent evidence suggests that marshes located in areas of low sediment loads (<20 mg L-1) will drown once a threshold of 0.5 cm year -1 of RSLR is attained (Kirwan et al. 2010). Specifically in the Northeast USA, shifting vegetation patterns indicative of wetter marsh platform (Warren and Niering 1993; Donnelly and Bertness 2001; Raposa et al. (submitted)) and widening channel networks (Hartig et al. 2002; Smith 2009; Watson et al. (submitted)) coupled with cycles in marsh pool formation (Wilson et al. 2014) and shifting marsh sediment structure (Wigand et al. 2014) provide evidence that marsh elevation may be lagging behind rates of RSLR.

Carey JC, Moran SB, Kelly RP, Kolker AS and RW Fulweiler. 2017. The declining role of organic matter in New England salt marshes. Estuaries and Coasts. 40(3): 626-639.

Enhanced aboveground production of plants from nutrient enrichment and fresh water also acts to promote trapping of sediments (Morris et al. 2002). Thus, a reduction of freshwater input due to climate change reduces, in a variety of ways, the ability of coastal plants to cope with sea level rise.

Day JW, Christian RR, Boesch DM, Yáñez-Arancibia A, Morris J, Twilley RR, Naylor L, Schaffner L and C Stevenson. 2008. Consequences of climate change on the ecogeomorphology of coastal wetlands. Estuaries and Coasts, 31, 477-491. doi: 10.1007/s12237-008-9047-6

In our marshes, there were two general mechanisms by which *S. patens* salt meadow was replaced by *S. alterniflora*. The first is the relatively slow landward encroachment of *S. alterniflora* into intact *S. patens* salt meadow that is likely driven by long-term sea level rise. The second is the more rapid, yet episodic, replacement via the formation and recovery of dieback patches.

> **Raposa KB, Weber RLJ, Cole Ekberg ML and W Ferguson. 2017. Vegetation dynamics in Rhode Island salt marshes during a period of accelerating sea level rise and extreme sea level events. Estuaries and Coasts. 40(3): 640-650.**

Although a number of factors can cause marsh vegetation dieback (Alber et al. 2008), we believe that the multi-year pulse documented in our marshes was a direct response to extreme high tides and elevated precipitation levels that led to prolonged periods of soil waterlogging.

> **Raposa KB, Weber RLJ, Cole Ekberg ML and W Ferguson. 2017. Vegetation dynamics in Rhode Island salt marshes during a period of accelerating sea level rise and extreme sea level events. Estuaries and Coasts. 40(3): 640-650.**

…, sea-level rise associated with climate change (by way of changes to atmospheric pressure, expansion of oceans and seas as they warm, and melting of ice sheets and glaciers) is one potentially significant process that is expected to play a role in sea water intrusion. The Intergovernmental Panel on Climate Change (IPCC 2001) predicts that by 2100, global warming will lead to a sea-level rise of between 110 and 880 mm, and it is generally understood that sea-level rise is expected to result in the inland migration of the mixing zone between fresh and saline water (FAO 1997). This is because the rise in sea water levels leads to increased saline water heads at the ocean boundary, and enhanced sea water intrusion is the logical consequence.

> **Werner AD and CT Simmons. 2009. Impact of Sea-Level rise on sea water intrusion in coastal aquifers. Ground Water. 47(2): 197-204. doi:10.1111/j.1745-6584.2008.00535.x**

The recent introduction of *D. spicata*, a marsh plant with wide ecological tolerance (Miller & Egler, 1950; Bertness & Ellison,
1987), may suggest that the Nauset Bay site is getting wetter. Warren and Niering (1993), studying a Long Island Sound marsh, suggest that conversion of a *S. patens* marsh to a wetter short *S. alterniflora*, *D. spicata*, and forbs community may be an indication that marsh accretion is not keeping up with sea-level rise. Further, they (Niering & Warren, 1980) suggest that colonization of marsh upland border communities with *D. spicata* may be attributed to rising sea level.

> **Roman CT, Peck JA, Allen JR, King JW and PG Appleby. 1997. Accretion of a New England (U.S.A.) salt marsh in response to inlet migration, storms, and sea-level rise. Estuarine, Coastal and Shelf Science 45: 717-727.**

In a regime of rising sea level, barrier beaches migrate landward primarily by overwash deposition and flood tidal-delta formation (Pierce, 1970; Dillon, 1970; Schwartz, 1975; Fig. 1).

> **Donnelly JP, Bryant SS, Butler J, Dowling J, Fan L, Hausmann N, Newby P, Shuman B, Stern J, Westover K and T Webb. 2001. 700 yr sedimentary record of intense hurricane landfalls in southern New England. GSA Bulletin 113(6):714-727.**

…, loss of high-marsh vegetation was apparent across all marsh systems. Some of this loss was related to changes in tidal regimes from inlet widening (artificial or natural). However, there are many systems that have not been altered in this way that similarly exhibited diminishing high-marsh vegetation. The most plausible explanation for this is sea-level rise—i.e., that tidal inundation is exceeding the flood tolerance of the species that grow there (Burdick 1989, Gleason and Zieman 1981).

Smith SM. 2009. Multi-decadal changes in salt marshes of Cape Cod, MA: Photographic analyses of vegetation loss, species shifts, and geomorphic change. Northeastern Naturalist 16(2):183-208.

About half of the high-marsh zones on Cape Cod retreated relatively slowly between 1947 and 1984, after which the rates accelerated. It is noteworthy that this time period overlaps with the 1989–1998 period of increased sea-level rise.

Smith SM. 2009. Multi-decadal changes in salt marshes of Cape Cod, MA: Photographic analyses of vegetation loss, species shifts, and geomorphic change. Northeastern Naturalist 16(2):183-208.

In conclusion, our model demonstrates the counterintuitive result that a salt marsh at its maximum productivity (i.e., at its optimum elevation and rate of RSLR) is not the most stable. Rather, a less productive marsh situated above its optimum elevation should be more stable because it will tolerate a higher RSLR and is less vulnerable to the variability in MSL.

Morris JT, Sundareshwar PV, Nietch CT, Kjerve B and DR Cahoon. 2002. Responses of coastal wetlands to rising sea level. Ecology 83(10): 2869-2877.

Across a range of century SLR rates, we demonstrated the important role of plant productivity on marsh resiliency. The tidal wetlands remained resilient to the pressures of increased sea level until reaching a tipping point where accommodation space, specifically adjacent upland habitat, was needed for maintenance of marsh habitat [6].

Schile LM, Callaway JC, Morris JT, Stralberg D, Parker VT and M Kelley. 2014. Modeling tidal marsh distribution with sea-level rise: Evaluating the role of vegetation, sediment, and upland habitat in marsh resiliency. PLoS ONE 9(2): e88760. Doi:10.1371/journal.pone.0088760

This study examined the independent and interactive effects of emerging threats to New England salt marshes (temperature increase, accelerating eutrophication, consumer-driven salt marsh die-off, and sea level rise) to understand the future trajectory of these ecologically valuable ecosystems…..Accelerating sea level rise and salt marsh die-off in particular may interact to overwhelm the compensatory mechanisms of marshes and increase their vulnerability to drowning. Management of marshes will require difficult decisions to balance ecosystem service tradeoffs and conservation goals, which, in light of the immediate threat of salt marsh loss, should focus on maintaining ecosystem resilience.

Gedan KB, Altieri AH and MD Bertness. 2011. Uncertain future of New England salt marshes? Marine Ecology-Progress Series 434:229-237.

There is concern that the rate of sea level rise will outpace the rate of accretion and salt marshes will drown. Sea level rise effects manifest in salt marshes in two different ways: 1) landward migration of salt marsh vegetation zones and submergence at lower elevations, and 2) interior ponding and marsh drowning.

Gedan KB, Silliman BR and MD Bertness. 2009. Centuries of human-driven change in salt marsh ecosystems. Annual Review of Marine Science 1: 117-141.

As a result of surface topography, water floods a marsh to different depths, resulting in larger vertical loading in areas of deeper flooding. Tidal flooding of 10 cm depth is sufficient to deform a salt marsh surface by both compression and lateral movement, resulting in uplift (Nuttle et al. 1990).

Cahoon DR, Hensel PF, Spencer T, Reed DJ , McKee KL and N Saintilan. 2006. Coastal wetland vulnerability to relative sea-level rise: Wetland elevation trends and process controls. Ecological Studies Vol.190 J.T.A.Verhoeven, B.Beltman, R.Bobbink,and D.F.Whigham (Eds.) Wetlands and Natural Resource Management © Springer-Verlag Berlin Heidelberg

Tidal salt marsh is a key defense against, yet is especially vulnerable to, the effects of accelerated sea level rise. To determine whether salt marshes in southern New England will be stable given increasing inundation over the coming decades, we examined current loss patterns, inundation-productivity feedbacks, and sustaining processes…Seaward retreat of the marsh edge, widening and headward expansion of tidal channel networks, loss of marsh islands, and the development and enlargement of interior depressions found on the marsh platform contributed to vegetation loss. Inundation due to sea level rise is strongly suggested as a primary driver…Growth experiments with Spartina alterniflora, the Atlantic salt marsh ecosystem dominant, across a range of elevations and inundation regimes further established that greater inundation decreases belowground biomass production of Spartina alterniflora, and thus negatively impacts organic matter accumulation. These results suggest that southern New England salt marshes are already experiencing deterioration and fragmentation in response to sea level rise, and may not be stable as tidal flooding increases in the future.

Watson EB, Wigand C, Davey EW, Andrews HM, Bishop J and KB Raposa. 2016. Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for Southern New England. Estuaries and Coasts DOI 10.1007/s12237-016-0069-1

An investigation of marsh accretion rates on a New England type high marsh (Barn Island Wildlife Management Area, Stonington, Connecticut) reveals that this system is sensitive to change in sea level and storm activity and the peat can accurately record rates of relative submergence as determined by tide gauge records over intervals of 2-5 decades. The results also suggest that the relationship between the accretion deficit and plant community structure is important when utilizing peat records to reconstruct historic sea-level curves within stable *Spartina pat*ens high marsh communities. In systems where major vegetation changes are prominent over short periods of time (<50 years), interpretations of sea-level rise should be limited to the system in which they are developed unless careful vertical controls can be maintained on the data and multiple datable horizons can be identified within the substrate. The results of this investigation further show that in a stable *Spartina patens* community within this particular system there is little vertical translocation of 137Cs, making this isotope a powerful tool for assessing rates of vertical marsh development since 1954.

Orson RA, Warren RS and WA Niering. 1998. Interpreting sea level rise and rates of vertical marsh accretion in a southern New England tidal salt marsh. Estuarine, Coastal and Shelf Science 47:419-429.

Lower surface elevations result in greater frequency and duration of tidal flooding, and thus in increased peat saturation, salinity, and sulfide concentrations, and in decreased redox potential, as directly measured over the growing season at both changed and stable sites. It is proposed that these edaphic changes have combined to favor establishment of a wetter, more open vegetation type dominated by two distinctive communities – stunted *S. alterniflora* and forbs.

Warren RS and WA Niering. 1993. Vegetation change on a northeast tidal marsh: interaction of sea-level rise and marsh accretion. Ecology 74(1):96-103.

Inundation due to sea level rise is strongly suggested as a primary driver: vegetation loss rates were significantly negatively correlated with marsh elevation ($r2=0.96$; $p=0.0038$), with marshes situated below mean high water (MHW) experiencing greater declines than marshes sitting well above MHW.

Watson EB, Wigand C, Davey EW, Andrews HM, Bishop J and KB Raposa. 2016. Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for Southern New England. Estuaries and Coasts DOI 10.1007/s12237-016-0069-1

Growth experiments with *Spartina alterniflora*, the Atlantic salt marsh ecosystem dominant, across a range of elevations and inundation regimes further established that greater inundation decreases belowground biomass production of *S. alterniflora* and, thus, negatively impacts organic matter accumulation.

Watson EB, Wigand C, Davey EW, Andrews HM, Bishop J and KB Raposa. 2016. Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for Southern New England. Estuaries and Coasts DOI 10.1007/s12237-016-0069-1

…, for minerogenic marshes, survival under a regime of rapid inundation increase is a function of sediment supply from local and watershed erosion (Kirwan et al. 2010). In contrast, for organic-rich marsh soils in southern New England, belowground productivity primarily determines whether marshes faced with accelerated SLR will aggrade or submerge.

Watson EB, Wigand C, Davey EW, Andrews HM, Bishop J and KB Raposa. 2016. Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for Southern New England. Estuaries and Coasts DOI 10.1007/s12237-016-0069-1

Productivity-elevation relationships show that *S. alterniflora* belowground growth varied as a function of orthometric height (Fig. 2). Plant growth was least robust at the lowest elevation and greatest inundation times. Highest biomass values were found at the highest elevations and lowest inundation times, both within and across sites.

Watson EB, Wigand C, Davey EW, Andrews HM, Bishop J and KB Raposa. 2016. Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for Southern New England. Estuaries and Coasts DOI 10.1007/s12237-016-0069-1

Inundation due to SLR is strongly indicated as a driver of vegetation loss. Plotting vegetation loss as a function of median marsh height relative to MHW (NTDE) (Fig. 8; r2 = 0.96; p = 0.0038), indicates that elevation, as a proxy for inundation, accounts for 96 % of the variability in loss rates.

Watson EB, Wigand C, Davey EW, Andrews HM, Bishop J and KB Raposa. 2016. Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for Southern New England. Estuaries and Coasts DOI 10.1007/s12237-016-0069-1

Coastal marsh vulnerability to loss driven by SLR is dependent on very specific local factors, including but not limited to, existing marsh elevation, macrophyte growth range and rooting profile, sediment availability, soil composition, local inundation regime, altered hydrology, and wave climate.

Watson EB, Wigand C, Davey EW, Andrews HM, Bishop J and KB Raposa. 2016. Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for Southern New England. Estuaries and Coasts DOI 10.1007/s12237-016-0069-1

…tidal range is a critical factor determining the vertical growth range of plant species in relation to local sea level. The larger the tidal range, the larger the growth range of the plant. Wetlands with a small tidal range will have a small growth range, and therefore a small potential to accumulate elevation capital, compared to wetlands with a large tidal and growth range.

Cahoon D and G Guntenspergen. 2010. Climate change, sea-level rise, and coastal wetlands. National Wetlands Newsletter, Vol. 32, No. 1, © 2010 Environmental Law Institute® Washington, DC, USA.

Wetlands that are beginning to deteriorate and convert to open water are not keeping pace, are at the bottom of the growth range for that setting, and are running out of elevation capital.

Cahoon D and G Guntenspergen. 2010. Climate change, sea-level rise, and coastal wetlands. National Wetlands Newsletter, Vol. 32, No. 1, © 2010 Environmental Law Institute® Washington, DC, USA.

The ephemeral nature of a salt marsh at the geological time scale indicates that these landforms are continuously recycled, destroyed, and reformed in a very dynamic coastal environment. The organic carbon sequestered in the peat is thus released in the ocean and new, younger organic material is subsequently stored in the sediments when the marsh reforms. This explanation is alternative to the common hypothesis that marshes formed only in the last 9000 yr, when relative rates of sea-level rise were slower (Rampino and Sanders, 1981).

Fagherazzi S. 2013. The ephemeral life of a salt marsh. Geology 41(8):943–944.

Based on the logistic regression model, the elevation threshold for S. patens presence was found to be 0.51mNAVD88: below 0.51mNAVD88, the model predicted S. patens absence, and above 0.51mNAVD88, the model predicted S. patens presence.

Watson EB, Szura K, Wigand C, Raposa KB, Blount K and M Cencer. 2016. Sea level rise, drought and the decline of Spartina patens in New England marshes. Biological Conservation 196:173-181.

Responses of tidal salt marshes were examined for the Sagamore Creek and Little Harbor Subareas. Under low rates of sea level rise by mid-century, most of our current low marsh may survive if it can accrete (build in elevation) at rates of 0.2 inches per year, or about half that of the sea level rise (0.34 inches per year). At higher rates of sea level rise (0.86 inches per year) and by the end of the century under either scenario, most, if not all of the low marsh will have submerged and converted to mudflat or subtidal bay. The current high marsh will convert to low marsh even under conditions of slow SLR, and high marsh will migrate upslope several feet (3.1 feet in elevation), where possible (along shorelines without barriers).

City of Portsmouth Planning Department. 2013. City of Portsmouth, New Hampshire, coastal resilience initiative. City of Portsmouth, NH. 85 p.

The combined effects of thermal expansion, increases in meltwater, a subsiding coast, and potential changes in ocean circulation make coastal New Hampshire particularly vulnerable to rising sea level. Increases in relative sea level contribute to enhanced 9ooding of coastal infrastructure, increased coastal erosion, saltwater contamination of freshwater ecosystems and loss of salt marshes and cordgrass. Low-lying shorelines such as sandy beaches and marshes are likely to be the most vulnerable to rising seas.

Wake CP, Burakowski E, Kelsey E, Hayhoe K, Stoner A, Watson C and E Douglas. 2011. Climate Change in the Piscataqua / Great Bay Region: Past, Present, and Future. Carbon Solutions New England, University of New Hampshire, Durham. 56 p.

Marsh elevations adjust to a step change in the rate of sea-level rise in about 100 years. In the case of a continuous acceleration in the rate of sea-level rise, modeled accretion rates lag behind sea-level rise rates by about 20 years, and never obtain equilibrium. Regardless of the style of acceleration, the models predict approximately 6–14cm of marsh submergence in response to historical sea-level acceleration, and 3–4cm of marsh submergence in response to a projected scenario of sea-level rise over the next century. While marshes already low in the tidal frame would be susceptible to these depth changes, our modeling results suggest that factors other than historical sea-level acceleration are more important for observations of degradation in most marshes today.

Kirwan M and S Temmerman. 2009. Coastal marsh response to historical and future sea-level acceleration. Quaternary Science Reviews. 28: 1801–1808.

Six plant species of New England salt marshes were studied: halophytes Spartina alterniflora, Spartina patens, and Juncus gerardii and brackish invasive species Phragmites australis, Typha angustifolia, and Lythrum salicaria. Plant shoots were transplanted across a gradient of three flooding and three salinity regimes and arranged into pair-wise competitive combinations. After one growing season, saltwater flooding was found to decrease transplant survival, biomass production, and/or relative growth for all species. Reduction in halophyte growth was largely due to increased flood duration; brackish species were most reduced by increased salinity.

Konisky RA and DM Burdick. 2004. Effects of stressors on invasive and halophytic plants of New England salt marshes: a framework for predicting response to tidal restoration. Wetlands 24:434-447

The goal of this study was to better understand how salt marsh sediment microbial communities may respond to sea level rise both functionally (decomposition rate) and compositionally (community structure). Evidence exists to suggest that biodiversity plays a role in keeping ecosystems resilient in the face of environmental change. This study examined whether community composition of salt marsh sediment microbes has a role in marsh response to anthropogenic stress. We collected sediment from two New England salt marshes and used a flow-through seawater lab to simulate sea level rise (SLR) and a terminal restriction fragment length polymorphism (t-RFLP) analysis to examine microbial community structure. Ultimately we found that an apparent link between microbial community functional response to SLR and shifts in community structure does exist. Microbial community diversity could thus be an important factor to consider when planning conservation and preservation efforts in the face of anthropogenic change.

Simon, MR. 2013. Effects of anthropogenic change on salt marsh sediment microbial community composition and function. Final Report, National Estuarine Research Reserve Graduate Research Fellowship, Grant Number: NA12NOS4200080. Great Bay NERR, 19 p.

…increased inundation caused a decrease in microbial community compositional shift that corresponded to a decline in decomposition rate. My results suggest that microbial functional response to SLR may be linked to changes in community composition.

Simon MR. 2013. East coast salt marsh response to sea level rise: microbial community function and structure. M.S. Thesis. University of New England, Biddeford, ME.. 42 p.

INCREASE IN EXTREME CLIMATE EVENTS

Storm tides, which can be several meters deep, can also deform the salt marsh surface (Cahoon 2003). The storm surge from Hurricane Andrew compressed the surface of a rapidly deteriorating salt marsh in Louisiana by 33 mm (Cahoon et al. 1995) and the deformed marsh surface had not rebounded 8 years later (Rybczyk and Cahoon 2002). In North Carolina, the surface of a salt marsh with 60 % soil organic matter content was compressed by 5–6 mm after each of two storms to strike the marsh in consecutive years. The deformed surface rebounded >10 mm the following year, only to be compressed 20 mm by another storm (Cahoon 2003).At these sites, the influence of water table fluctuations, organic substrates, and pre- existing marsh deterioration all appear to have influenced the compression of the substrate. However, the mechanism driving the potential rebound of such deformed surfaces is not known.

Cahoon, D.R., Hensel, P.F., Spencer, T, Reed, D.J., McKee, K.L. and N. Saintilan. 2006. Coastal wetland vulnerability to Cahoon DR, Hensel PF, Spencer T, Reed DJ , McKee KL and N Saintilan. 2006. Coastal wetland vulnerability to relative sea-level rise: Wetland elevation trends and process controls. Ecological Studies Vol.190 J.T.A.Verhoeven, B.Beltman, R.Bobbink,and D.F.Whigham (Eds.) Wetlands and Natural Resource Management © Springer-Verlag Berlin Heidelberg

A synthesis of existing literature is presented and shows that ECE [extreme climatic events; droughts, floods, tropical cyclones, heat waves] affect estuarine water quality by altering: (1) the delivery and processing of nutrients and organic matter, (2) physical–chemical properties of estuaries, and (3) ecosystem structure and function.

Wetz MS and DW Yoskowitz. 2013. An 'extreme' future for estuaries? Effects of extreme climatic events on estuarine water quality and ecology. Marine Pollution Bulletin 69:7-18.

Despite generally positive effects on estuarine water quality, low freshwater inflow events may still have deleterious effects on living resources. Most apparent are effects of these events on the physical–chemical conditions in estuaries (e.g., salinity, marsh chemistry, etc.) and subsequent implications for habitat suitability. For example, several recent studies have noted dieback of salt marsh grasses during droughts Mckee et al., 2004; Alber et al., 2008). Although the cause of these diebacks is unknown, at least one study suggested that there are direct and negative effects of drought on marsh grass physiology (Brown et al., 2006).

Wetz MS and DW Yoskowitz. 2013. An 'extreme' future for estuaries? Effects of extreme climatic events on estuarine water quality and ecology. Marine Pollution Bulletin 69:7-18.

Invasive and Nuisance Species

CURRENT CONDITION

Differences in *Sesarma* grazing pressure and associated crab density explained >80% of intermarsh variation in the extent of die-off of Cape Cod salt marshes, and crab exclusions demonstrated experimentally that the extensive cordgrass die-offs in Cape Cod salt marshes are driven by crab herbivory.

Holdredge C, Bertness MD and AH Altieri. 2008. Role of crab herbivory in die-off of New England salt marshes. Conservation Biology 23 (3): 672-679.

Our results provide compelling evidence that grazing pressure by a common, native crab, *Sesarma reticulatum* is leading to the loss of cordgrass and the current die-off of saltmarshes on Cape Cod, Massachusetts. These results contribute to growing evidence that human disturbances are triggering increased consumer control in salt marshes and driving these ecosystems to collapse throughout the western Atlantic.

Holdredge C, Bertness MD and AH Altieri. 2008. Role of crab herbivory in die-off of New England salt marshes. Conservation Biology 23 (3): 672-679.

Although bottom-up, physical factors have long been thought to control salt marsh productivity (e.g., Teal 1962; Odum 1969; Nixon 1982), results from our study and studies of a diversity of other marsh ecosystems from the Canadian sub- Arctic (Jefferies 1997) to the southeastern coast of the United States (Silliman et al. 2005) and Argentina (Alberti et al. 2008) suggest that human activities, such as overfishing and eutrophication, are stimulating consumer densities and their impacts. This shift toward strong top-down, consumer control is precipitating large-scale vegetation die-offs (Bertness & Silliman 2008).

Holdredge C, Bertness MD and AH Altieri. 2008. Role of crab herbivory in die-off of New England salt marshes. Conservation Biology 23 (3): 672-679.

Genotypes of the grass *Phragmites australis* introduced to North America from Europe are likely to stabilize tidal wetlands because of traits that support higher below-ground productivity than the vegetation they are replacing (Rooth et al. 2000; Mozdzer & Megonigal 2012).

Kirwan, ML and P Megonigal. 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504: 53-60.

Shoreline development, operationally defined as removal of the woody vegetation bordering marshes, explained >90% of intermarsh variation in *Phragmites* cover. Shoreline development was also significantly correlated with reduced soil salinities and increased nitrogen availability, suggesting that removing woody vegetation bordering marshes increases nitrogen availability and decreases soil salinities, thus facilitating *Phragmites* invasion.

Silliman BR and MD Bertness. 2004. Shoreline development drives invasion of Phragmites australis and the loss of plant diversity on New England salt marshes. Conservation Biology 18(5): 1424-1434.

All *Phragmites australis* populations on the Rhode Island mainland were found to be exotic, but native populations were found on Block Island in tidal marsh habitats. At the time of writing, some native *Phragmites* patches were being overtaken by stands of exotic *Phragmites*.

Lambert AM and RA Casagrande. 2006. Distribution of native and exotic Phragmites australis in Rhode Island. Northeastern Naturalist 13(4): 551-560.

The authors surveyed 22 salt marshes in Narragansett Bay to test for relationships between shoreline development (removal of the woody vegetation buffer between marshes and the upland), N availability, soil salinity, and *Phragmites* cover. Shoreline development was associated with lowered soil salinity and increased nitrogen availability known to exacerbate *Phragmites* invasion, and was found to explain over 90% of *Phragmites* cover variability between marshes.

Silliman BR and MD Bertness. 2004. Shoreline development drives invasion of Phragmites australis and the loss of plant diversity on New England salt marshes. Conservation Biology 18(5): 1424-1434.

The authors performed field surveys at 11 recovering and 5 healthy marsh creek bank sites, measuring total *Spartina alterniflora*, die-off, and recovery zone widths. *Carcinus* abundance was quantified along transects at all sites. A burrow competition experiment was performed: mesocosms containing a *Sesarma* burrow contained whether *Sesarma* only or *Sesarma* and *Carcinus* were scored (*Sesarma* in or out of burrow) after overnight trials. Survey findings suggested that *Carcinus* density was positively correlated with vegetation regrowth, and the burrow competition experiment demonstrated that *Carcinus* preys on *Sesarma* and evicts *Sesarma* from burrows. Therefore, *Carcinus* may promote *S. alterniflora* recovery.

Bertness MD and TC Coverdale. 2013. An invasive species facilitates the recovery of salt marsh ecosystems on Cape Cod. Ecology 94.9 (2013): 1937-1943.

The introduced *Hemigrapsus sanguineus* has recently been observed in salt marshes, a novel ecosystem for this typically subtidal crab. In this study, the authors first performed a burrow competition experiment (*Hemigrapsus* vs. *Uca pugilator*) in both mesocosms and the field. A second experiment was carried out to determine effects of *Hemigrapsus* and *Carcinus maenus* on ribbed mussels. Results indicate that *Hemigrapsus* was able to displace *Uca* from borrows, and that at high densities, *Hemigrapsus* decreased number and biomass of ribbed mussels consumed by *Carcinus*. When crabs foraged together, they consumed smaller mussels than when foraging separately. These findings have implications for potential impacts of *Hemigrapsus* invasion on salt marsh structure and function.

Peterson BJ, Fournier AM, Furman BT and JM Carroll. 2014. Hemigrapsus sanguineus in Long Island salt marshes: experimental evaluation of the interactions between an invasive crab and resident ecosystem engineers. PeerJ 2 (2014): e472.

Research on impacts of climate change on plant diseases has been limited, with most work concentrating on the effects of a single atmospheric constituent or meteorological variable on the host, pathogen, or the interaction of the two under controlled conditions. Results indicate that climate change could alter stages and rates of development of the pathogen, modify host resistance, and result in changes in the physiology of host-pathogen interactions. The most likely consequences are shifts in the geographical distribution of host and pathogen and altered crop losses, caused in part by changes in the efficacy of control strategies. Recent developments in experimental and modeling techniques offer considerable promise for developing an improved capability for climate change impact assessment and mitigation. Compared with major technological, environmental, and socioeconomic changes affecting agricultural production during the next century, climate change may be less important; it will, however, add another layer of complexity and uncertainty onto a system that is already exceedingly difficult to manage on a sustainable basis. Intensified research on climate change–related issues could result in improved understanding and management of plant diseases in the face of current and future climate extremes.

Coakley SM, Scherm H and S Chakraborty. 1999. Climate change and plant disease management. Annual Review of Phytopathology. 37: 399-426.

Predator depletion on Cape Cod (USA) has released the herbivorous crab *Sesarma* reticulatum from predator control leading to the loss of cordgrass from salt marsh creek banks. After more than three decades of die-off, cordgrass is recovering at heavily damaged sites coincident with the invasion of green crabs (*Carcinus maenas*) into intertidal *Sesarma* burrows. We hypothesized that *Carcinus* is dependent on *Sesarma* burrows for refuge from physical and biotic stress in the salt marsh intertidal and reduces *Sesarma* functional density and herbivory through consumptive and non-consumptive effects, mediated by both visual and olfactory cues. Our results reveal that in the intertidal zone of New England salt marshes, *Carcinus* are burrow dependent, *Carcinus* reduce *Sesarma* functional density and herbivory in die-off areas and *Sesarma* exhibit a generic avoidance response to large, predatory crustaceans. These results support recent suggestions that invasive *Carcinus* are playing a role in the recovery of New England salt marshes and assertions that invasive species can play positive roles outside of their native ranges.

Coverdale TC, Axelman EE, Brisson CP, Young EW, Altieri AH and MD Bertness. 2013. New England salt marsh recovery: Opportunistic colonization of an invasive species and its non-consumptive effects. PLoS ONE 8(8): e73823. doi:10.1371/journal.pone.0073823

Models project that warmer climates with increased winter precipitation will affect trees directly and also indirectly through effects on nuisance species, such as insect pests, pathogens, and invasive plants. Several of these species are likely to have stronger or more widespread effects on community composition and structure under the projected climate. However, uncertainty pervades our predictions and uncertainty will always persist.

Dukes JS, Pontius J, Orwig D, Garnas JR, Rodgers VI, Brazee N, Cooke B, Theoharides KA, Stange EE, Harrington R, Ehrenfeld J, Gurevitch J, Lerdau M, Stinson K, Wick R and M Ayres. 2009. Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? Canadian Journal of Forest Research. 39(2): 231-248.

Scientific and societal unknowns make it difficult to predict how global environmental changes such as climate change and biological invasions will affect ecological systems. In the long term, these changes may have interacting effects and compound the uncertainty associated with each individual driver. Nonetheless, invasive species are likely to respond in ways that should be qualitatively predictable, and some of these responses will be distinct from those of native counterparts. We used the stages of invasion known as the “invasion pathway” to identify 5 nonexclusive consequences of climate change for invasive species: (1) altered transport and introduction mechanisms, (2) establishment of new invasive species, (3) altered impact of existing invasive species, (4) altered distribution of existing invasive species, and (5) altered effectiveness of control strategies. We then used these consequences to identify testable hypotheses about the responses of invasive species to climate change and provide suggestions for invasive-species management plans. The 5 consequences also emphasize the need for enhanced environmental monitoring and expanded coordination among entities involved in invasive-species management.

Hellmann JJ, Byers JE, Bierwagen BG and JS Dukes. 2008. Five potential consequences of climate change for invasive species. Conservation Biology. 22(3): 534-543.

Deer can alter the structure and composition of communities via both direct and indirect mechanisms. Deer may limit the regeneration of favored and susceptible woody plants and eliminate populations of favored or susceptible herbaceous plants. This may affect other populations. Baseline data from 50 years ago indicate that some communities are changing in a pattern that implicates deer: grasses, sedges, and some ferns are increasing while overall herb diversity is declining. Deer are playing a keystone role in some communities.

Rooney TP and DM Waller. 2003. Direct and indirect effects of white-tailed deer in forest ecosystems. Forest Ecology and Management. 18(1-2): 165-176.

In a manipulative experiment in which the amount of Phragmites australis litter was varied from 250 g DWm–2 to 2000 g DWm–2, the amount of trapped sediment increased exponentially (Rooth et al. 2003). The combined effect of reducing flows and stabilising the substrate may lead to a positive relationship between vegetative aboveground biomass and marsh elevation change, although few studies have shown this link experimentally.

Cahoon DR, Hensel PF, Spencer T, Reed DJ , McKee KL and N Saintilan. 2006. Coastal wetland vulnerability to relative sea-level rise: Wetland elevation trends and process controls. Ecological Studies Vol.190 J.T.A.Verhoeven, B.Beltman, R.Bobbink,and D.F.Whigham (Eds.) Wetlands and Natural Resource Management © Springer-Verlag Berlin Heidelberg

Introduced Phragmites is probably the most common invasive species in our coastal marshes and has been the subject of much research regarding its impacts on marsh communities. To help resource managers and scientists identify the morphological differences between native and non-native Phragmites, a workshop, entitled Field Identification of Phragmites australis and Phragmites australis americanus in New England, was held at the Great Bay National Estuarine Research Reserve. The current understanding of the ecology of both native and non-native Phragmites is also discussed, followed by a description of on-going work. Finally, a step by step guide to developing an effective Phragmites management strategy is provided to aid decision-makers in determining the best course of action.

Saltonstall K, Burdick D, Miller S and B Smith. 2005. Native and Non-native Phragmites: Challenges in Identification, Research, and Management of the Common Reed. National Estuarine Research Reserve Technical Report Series 2005. 40 p.

INCREASE IN CO_2

Using a greenhouse experiment, the authors tested the effect of elevated atmospheric CO2 (700 ppm) and temperatures (+5C) and soil salinity on 2 *Phragmites australis* phenotypes. Soil salinity is a known stressor of *Phragmites*, but effects were significantly less severe under conditions of elevated Co2 and temperature. These findings suggest that under future climatic states, *Phragmites* may be able to invade more saline areas (encroach further into salt marshes).

Eller F, Lambertini C, Nguyen LX and H Brix. 2014. Increased invasive potential of non-native Phragmites australis: elevated CO2 and temperature alleviate salinity effects on photosynthesis and growth. Glob change boil. 20(2): 531-543.

Using open-top chambers in a brackish salt marsh at the Smithsonian Research Center, the authors used a factorial design to test effects of elevated atmospheric CO2 (about 700 ppm) and N enrichment (25 g N m-2yr-1) on *Phragmites* productivity. CO2 and N enrichments increased gross primary production by 44% and 60%, but mechanisms for these increases differed. CO2 enrichment stimulated productivity during the early and mid growing season, and N enrichment stimulated productivity early and late in the growing season. Under CO2 and N conditions, gross primary productivity was increased by 95% relative to controls.

Caplan JS, Hager RN, Megonigal JP and TJ Mozdzer. 2015 Global change accelerates carbon assimilation by a wetland ecosystem engineer. Environmental Research Letters 10(2015): 115006.

We found a clear dichotomy in the effects of elevated CO_2 on shoot %N in the C3 and C4 species. Increasing CO_2 reduced green tissue %N in the C3 sedge *Scirpus olneyi* but had no effect on the C4 grasses *Spartina patens* or *Distichlis spicata*.

Curtis PS, Drake BG and DF Whigham. 1989. Nitrogen and carbon dynamics in C3 and C4 estuarine marsh plants grown under elevated CO2 in situ. Oecologia 78(3): 297-301.

The reduction in %N of *Scirpus* shoots resulted in an increase in green tissue C/N ratios of between 20 and 40%. Insect herbivores respond to changes in the relative amount of N in leaves by altering their feeding behavior and the amount of tissue consumed (Scriber 1984).

Curtis PS, Drake BG and DF Whigham. 1989. Nitrogen and carbon dynamics in C3 and C4 estuarine marsh plants grown under elevated CO2 in situ. Oecologia 78(3): 297-301.

A shift in insect feeding preference away from Scirpus, or alternatively, a greater consumption of Scirpus tissue to meet nutritional demands could have important consequences for plant species interactions and community composition (McBrien et al. 1983).

Curtis PS, Drake BG and DF Whigham. 1989. Nitrogen and carbon dynamics in C3 and C4 estuarine marsh plants grown under elevated CO2 in situ. Oecologia 78(3): 297-301.

Root tissue % N decreased and the C/N ratio increased in the *Scirpus* community under elevated CO_2 (Fig. 4). Similar results had been found previously in *Scirpus* shoot tissue (Curtis et al. 1989b). Such changes in elemental composition can have significant effects on herbivore preference and feeding rates (Lincoln et al. 1986, Fajer et al. 1989). While root herbivores are probably not abundant in anaerobic peat, these changes in tissue composition could influence decomposition rates. Increasing tissue C/N ratio decreases the decomposition rate (Melillo et al. 1984, Taylor et al. 1989). Greater root growth combined with slower decomposition would tend to increase carbon accretion and peat formation in wetland communities containing *Scirpus olnevi*.

Curtis PS, Balduman LM, Drake BG and DF Whigham. 1990. Elevated atmospheric CO2 effects on belowground processes in C3 and C4 estuarine marsh communities. Ecology 71(5): 2001-2006.

CHANGE IN TEMPERATURE

Using a greenhouse experiment, the authors tested the effect of elevated atmospheric CO2 (700 ppm) and temperatures (+5C) and soil salinity on 2 *Phragmites australis* phenotypes. Soil salinity is a known stressor of *Phragmites*, but effects were significantly less severe under conditions of elevated Co2 and temperature. These findings suggest that under future climatic states, *Phragmites* may be able to invade more saline areas (encroach further into salt marshes).

Eller F, Lambertini C, Nguyen LX and H Brix. 2014. Increased invasive potential of non-native Phragmites australis: elevated CO2 and temperature alleviate salinity effects on photosynthesis and growth. Glob change boil. 20(2): 531-543.

CHANGE IN SEA LEVEL

… whereas the *S. patens* decline in our study was primarily due to replacement by *S. alterniflora*, there was less evidence of impacts from encroaching *S. alterniflora* on outer Cape Cod where flooding stress and crab herbivory both contributed to high marsh dieback (Smith et al. 2012). This indicates that multiple stressors may be acting synergistically to drive the loss of *S. patens* salt meadow from southern New England salt marshes.

Raposa KB, Weber RLJ, Cole Ekberg ML and W Ferguson. 2017. Vegetation dynamics in Rhode Island salt marshes during a period of accelerating sea level rise and extreme sea level events. Estuaries and Coasts. 40(3): 640-650.

Results revealed mean salinity values were significantly different between each of the community categories sampled within the Estuary. Due to management concerns over expansion of Phragmites within the Estuary, we mapped the salinity range for this community and provided graphic and numerical estimates of potential Phragmites habitat based on salinity alone (26% of the total acreage surveyed).

Moore GE, Burdick DM, Peter CR and DR Keirstead. 2011. Mapping soil pore water salinity of tidal marsh habitats using electromagnetic induction in Great Bay Estuary, USA. Wetlands, DOI 10.1007/s13157-010-0144-5. Springer, 10 p.

Our field study associated natural variability in soil salinity levels over time and space with vigor and spread rates of *P. australis*. Our results indicated that salinity in tidal marshes varied temporally due to the extent of tidal flooding (salinity was greater during spring tides compared with neap tides) and regional freshwater runoff (salinity was lower in the spring). If the growing season is split into early (May–July) and late (August–October) periods, interesting patterns emerged (salinity increased with depth early, but decreased with depth late). In general, the stands of *P. australis* were expanding into salt marsh at 0.35 m per year, and increasing in cover (8% per year), even though the canopy height decreased at all but two of the sites over the study period. Salinity was lower in marshes where tides were artificially restricted (11–16 ppt compared with 19–24 ppt for the natural marshes), and one of these sites exhibited rapid *P. australis* expansion. At sites with natural hydrology, *P. australis* appeared to be expanding more slowly, shading out marsh species, and perhaps avoiding salinity stress by accessing natural sources of fresher water at different soil depths during different seasons.

Burdick DM, Buchsbaum R and E Holt. 2001. Variation in soil salinity associated with expansion of Phragmites australis in salt marshes. Environ. Exp.Botany 46(3):247-261.

The descriptive study shows that restricted flooding from berm interference can result in significantly altered physical gradients in addition to landward subsidence and pool development. The results from the transplant experiment indicate that the altered landward structure affects the relative importance of biological interactions, namely herbivory, in controlling plant species distribution. The predictive GIS analyses illustrate the location of 34 berm sites within the Great Bay Estuary and highlight the bermed marshes most at risk of invasion by the non-native variety of Phragmites australis and submergence during sea level rise. Based on the combined findings, berms have the potential to reduce the overall biodiversity and integrity of tidal marshes.

Mora JW. 2011. The effects of historic earthen barriers on Northern New England tidal marshes. National Estuarine Research Reserve Graduate Research Fellowship, Final Report. Grant Number: NA09NOS4200040, Sponsoring Reserve: Great Bay, NH. 247 p.

Nutrients

CURRENT CONDITION

We expected that the marshes exposed to higher N concentrations would have lower accretion rates as a result of increasing decomposition rates and declining geomorphic stability (Deegan et al. 20012). However, we found no relationship (R2<0.01) between N availability in the water column, aboveground biomass, or belowground MOM [macro- organic matter] (Table 1) and accretion rates in these marshes.

Carey JC, Moran SB, Kelly RP, Kolker AS and RW Fulweiler. 2017. The declining role of organic matter in New England salt marshes. Estuaries and Coasts. 40(3): 626-639.

Plants grown under nutrient-enriched conditions were associated with a decreased abundance of coarse roots (≥1 mm < 2 mm; F=30.67, p<0.001) and rhizomes (F=7.43, p=0.0098). As fine roots are labile and turn over rapidly (Morris et al. 2013), these results suggest that nutrient-enrichment adversely affects long-term [organic matter] accumulation. Additionally, elevated nutrient concentrations stimulated below-ground decomposition, a key process in the organic-rich marsh soils.

Watson EB, Oczkowski AJ, Wigand C, Hanson AR, Davey EW, Crosby SC, Johnson RL and HM Andrews. 2014. Nutrient enrichment and precipitation changes do not enhance resiliency of salt marshes to sea level rise in the Northeastern U.S. Climatic Change 125:501-509. DOI 10.1007/s10584-1189-x

Nitrogen eutrophication is stimulated by shoreline development (as N inputs increase and woody buffers are removed) and releases plants from competition for nitrogen. Competition, along with ability to tolerate the stresses of inundation and high salinities, structures salt marsh vegetation communities. As a result of eutrophication, *Spartina alterniflora* was shown to shift landward and *Phragmites australis* encroached from the landward marsh edge, displacing native high marsh vegetation communities.

Bertness MD, Ewanchuk PJ and BR Silliman. 2002. Anthropogenic modification of New England salt marsh landscapes. Proceedings of the National Academy of Sciences 99(3): 1395-1398.

Nitrate-N and phosphate were added via tidal flood water to a previously unimpacted marsh ecosystem for 9 years at levels 15 and 5 times the site background, respectively. As a result, aboveground biomass increased, belowground biomass decreased, and organic matter decomposition accelerated. As a result, marsh geomorphic stability was lost, and creek bank marsh collapse was observed by year 7.

Deegan LA, Johnson DS, Warren RS, Peterson BJ, Fleeger JW, Fagherazzi S and WM Wolheim. 2012. Coastal eutrophication as a driver of salt marsh loss. Nature 490: 388-392.

Nitrate-N was added to a *Spartina patens* plot in 500 mL pulses at rates of 1.4 g m-2, within range of groundwater nitrate concentrations from the US east coast. These N pulses stimulated significantly greater emission of the potent greenhouse gas nitrous oxide than from control plots. As nitrate has a global warming potential over 300 times that of carbon dioxide, its emission could offset marsh carbon sequestration. Studies of nitrous oxide flux dynamics in response to long-term N enrichment is needed.

Moseman-Valtierra S, Gonzalez R, Kroeger KD, Tang J, Chao WC, Crusius J, Bratton J, Green A and J Shelton. 2011. Short-term nitrogen additions can shift a coastal wetland from a sink to a source of N2O. Atmospheric Environment 45(26): 4390-4397.

The authors measured marsh accretion rates and soil organic content in response to long-term fertilization (over 4 decades) at Great Sippewisset Marsh (Valiela et al.,1975). Nutrient amendments did not increase marsh soil accretion rates and decreased organic matter accumulation below 25 cm. There was no effect of nutrient addition in the upper 25 cm. Marsh shear vane strength was lower with less organic carbon present, a finding with implications for marshes' ability to resist erosion.

Turner RE, Howes BL, Teal JM, Milan CS, Swenson EM and DD Goehringer-Tonerb. 2009. Salt marshes and eutrophication: An unsustainable outcome. Limnology and Oceanography 54(5): 1634-1642.

The authors studied plant species richness and *Spartina patens* and *Spartina alterniflora* metrics in Narragansett Bay marshes along gradients of nitrogen (estimated loadings ranging from 2-10,253 kg N ha-1 yr-1) and development. At marshes (n=5) with similar slopes, nitrogen load had a significant negative correlation with S. patens and a significant positive correlation with *S. alterniflora.*

Wigand C, McKinney RA, Charpentier MA, Chintala MM and GB Thursby. 2003. Relationships of nitrogen loadings, residential development, and physical characteristics with plant structure in New England salt marshes. Estuaries 26(6): 1494-1504.

Morris et al. (2002), for example, found that nutrient enrichment increased production and standing biomass of salt marsh plants, which accelerated elevation gain by increased sediment trapping from 5.1 mm year–1 to 7.1 mm year–1.

Cahoon DR, Hensel PF, Spencer T, Reed DJ , McKee KL and N Saintilan. 2006. Coastal wetland vulnerability to relative sea-level rise: Wetland elevation trends and process controls. Ecological Studies Vol.190 J.T.A.Verhoeven, B.Beltman, R.Bobbink, and D.F.Whigham (Eds.) Wetlands and Natural Resource Management © Springer-Verlag Berlin Heidelberg

According to both our modeling results, modest watershed conservation efforts as defined by our expert stakeholders, ie: protecting wetlands and forests, could reduce the amount of total nitrogen entering the Great Bay [NH] estuary in the range of 3–28 metric tons per year.

Berg CE, Mineau MM and SH Rogers. 2016. Examining the ecosystem service of nutrient removal in a coastal watershed. Ecosystem Services 20:104–112.

Coastal nutrient addition/enrichment, which is widespread and ongoing, may lower root and rhizome biomass, belowground production and organic accumulation in this species. Higher soil respiration and a lower Eh (redox potential) are expected additional soil property changes. The addition of P, more than of N, seems to reduce root and rhizome biomass accumulation. The cumulative effects of increased nutrient loadings on salt marshes may be to decrease soil elevation and accelerate the conversion of emergent plant habitat to open water, particularly on the lower marsh.

Darby FA and RE Turner. 2008. Effects of eutrophication on salt marsh root and rhizome biomass accumulation. Marine Ecology Progress Series. 363: 63-70.

Functional redundancy in bacterial communities is expected to allow microbial assemblages to survive perturbation by allowing continuity in function despite compositional changes in communities. Recent evidence suggests, however, that microbial communities change both composition and function as a result of disturbance. We present evidence for a third response: resistance. We examined microbial community response to perturbation caused by nutrient enrichment in salt marsh sediments using deep pyrosequencing of 16S rRNA and functional gene microarrays targeting the *nirS* gene. Composition of the microbial community, as demonstrated by both genes, was unaffected by significant variations in external nutrient supply in our sampling locations, despite demonstrable and diverse nutrient-induced changes in many aspects of marsh ecology. The lack of response to external forcing demonstrates a remarkable uncoupling between microbial composition and ecosystem-level biogeochemical processes and suggests that sediment microbial communities are able to resist some forms of perturbation.

Bowen JL, Ward BB, Morrison HG, Hobbie JE, Valiela I, Deegan LA and ML Sogin. 2011. Microbial community composition in sediments resists perturbation by nutrient enrichment. The ISME journal. 5(9): 1540-1548.

We hypothesized that adding nitrogen in these detritus-rich systems would directly stimulate bacterial decomposition of marsh peat. Contrary to our expectations, we found no response to added nutrients in high marsh habitats, where there is a significant supply of organic matter from marsh vegetation. Bacterial production did increase in the low marsh habitats, where fertilization increased the standing stock of benthic chlorophyll. Fertilization did not directly increase bacterial production by providing added nutrients that could be used to decompose organic matter derived from nutrient-poor marsh grasses. Rather, bacterial productivity was indirectly stimulated by the concomitant increase in labile benthic microalgae in low marsh habitats. Decomposition of salt marshes may therefore have a greater resilience to the threat of chronic eutrophication than has been previously recognized.

Bowen JL, Crump BC, Deegan LA and JE Hobbiec. 2009. Increased supply of ambient nitrogen has minimal effect on salt marsh bacterial production. Limnol. Oceanogr. 54(3):713–722.

INCREASE IN CO_2

The authors selected 4 species (*Phragmites australis, Typha angustifolia, Spartina alterniflora, Leersia oryzoides*) along a continuum of invasiveness in order to test whether species varied consistently in growth and success metrics. The authors found that *Phragmites* had significantly greater leaf nitrogen levels than all other species, a finding with implications for marsh nitrogen cycling under invaded conditions.

Farnsworth EJ and LA Meyerson. 2003. Comparative ecophysiology of four wetland plant species along a continuum of invasiveness. Wetlands 23(4): 750-762.

**Placed in the CO2 section because as a C3 plant, Phragmites invasion may be enhanced by elevated atmospheric CO2 concentrations (See Eller et al., 2014).

The authors manipulated atmospheric CO2 (raised to 720 ppm) and fertilized with ammonium-N (25 g N m-2 yr-1) in a factorial design in a Chesapeake Bay marsh to test the hypothesis that nitrogen limitation constrains ecosystem response to elevated CO2. Findings indicated that although N enrichment allowed plants to better respond to CO2 enrichment after a year of treatment, plant community composition was shifted by N enrichment to favor a shift in plant community composition that decreased overall CO2-stimulated productivity by year 3.

Langley JA and JP Megonigal. 2010. Ecosystem response to elevated CO2 levels limited by nitrogen-induced plant species shift. Nature 466: 96-99.

…results suggest that the plants follow resource capture theory. The C3 species increased aboveground productivity under the added N and elevated CO_2 treatment ($P < 0.0001$), but did not under either added N or elevated CO_2 alone. C3 fine root production decreased with added N ($P < 0.0001$), but fine roots increased under elevated CO_2 ($P = 0.0481$).

White KP, Langley JA, Cahoon DR and JP Megonigal. 2012. C3 and C4 Biomass Allocation Responses to

Elevated CO2 and Nitrogen: Contrasting Resource Capture Strategies. Estuaries and Coasts, 35(4): 1028-1035. doi:10.1007/s12237-012-9500-4

The C4 species increased growth under high N availability both above- and belowground, but that stimulation was diminished under elevated CO_2.

White KP, Langley JA, Cahoon DR and JP Megonigal. 2012. C3 and C4 Biomass Allocation Responses to Elevated CO2 and Nitrogen: Contrasting Resource Capture Strategies. Estuaries and Coasts, 35(4): 1028-1035. doi:10.1007/s12237-012-9500-4

…, our results suggest that mineral rich marshes may be able to trap more sediment with greater shoot growth under high N loading. However, N loading may reduce rates of soil accumulation in highly organic marshes, where the system depends on the deposition of organic matter belowground, not only by reducing allocation to roots in individual plants (as found by Turner 2011) but also by shifting community composition to species that innately produce less belowground matter.

White KP, Langley JA, Cahoon DR and JP Megonigal. 2012. C3 and C4 Biomass Allocation Responses to Elevated CO2 and Nitrogen: Contrasting Resource Capture Strategies. Estuaries and Coasts, 35(4): 1028-1035. doi:10.1007/s12237-012-9500-4

INCREASE IN TEMPERATURE

The authors manipulated precipitation and warming to test effects of future climatic states on salt marsh vegetation in a Plum Island Estuary salt marsh. Five treatments were tested: doubled precipitation, decreased precipitation (drought), warming, warming plus doubled precipitation, and control. Temperatures in the warmed treatment were increased between 0.89 and 2.77C. Warming increased aboveground biomass for *Spartina alterniflora* but not high marsh species (*S. patens* and *D. spicata*) and increased maximum stem heights for all 3 species. Warming accelerated decomposition associated with the *S. patens* community, and drought decreased decomposition for native high marsh species. Drought increased total biomass for *S. alterniflora* and *S. patens*. In *S. alterniflora*, nitrogen mineralization was greatest under drought simulation but not affected by doubled precipitation.

Charles H and JS Dukes. 2009. Effects of warming and altered precipitation on plant and nutrient dynamics of a New England salt marsh. Ecological Applications 19(7): 1758-1773.

CHANGE IN PRECIPITATION

See also Charles and Dukes 2009 above (Nutrients/Increase in Temperature)

Typically, the amount of N added in experimental treatments simulates total N input and therefore far exceeds the amount that U.S. intertidal wetlands would receive by atmospheric deposition. Only two studies (Table 17.3) have addition levels below 100 kg N ha-1 yr -1. Based on the results of Wigand et al. (2003), a critical load to protect the community structure of salt marshes is likely to be 63 to 400 kg N ha-1 yr -1. Caff rey et al. (2007) provide additional evidence that 80 kg N ha-1 yr -1 alters microbial activity and biogeochemistry. Latimer and Rego (2010) found that eelgrass coverage started to decrease rapidly at N loading higher than 50 kg N ha-1 yr-1, with no eelgrass at loading levels higher than 100 kg N ha-1 yr-1. Note that these values are the total N loading to salt marshes, including N deposition directly to the marsh surface, as well as N deposited indirectly to the watershed, surface or ground water, and runoff from agriculture, urban areas, and other sources.

Pardo LH, Robin-Abbott MJ and CT Driscoll. 2011. Assessment of Nitrogen deposition effects and empirical critical loads of nitrogen for ecoregions of the United States. U.S. Forest Service, Newtown Square, PA. 301 p.

CHANGE IN SEA LEVEL

Deterioration of tidal wetlands often begins with plant stress, and the disruption of the stabilizing feedbacks that plants provide. …Even temporary, climatically driven episodes of vegetation die-off (Silliman et al. 2005; Alber et al. 2008) sometimes lead to geomorphic change, including rapid subsidence, platform erosion and diminished deposition rates (Temmerman et al. 2012; Baustian et al. 2012). Thus factors that influence the growth rate of plants (for example, climate and nutrients) are likely to influence the ability of a marsh to survive sea-level rise.

Kirwan, ML and P Megonigal. 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504: 53-60.

This paper reports effects of sea level rise and fertilization on the experimental plots at Great Sippewisset Marsh when fertilization had been taking place for 28 years. Fertilization had resulted in a change in vegetation community composition, with the originally dominant short-form *S. alterniflora* being replaced by other species, most notably tall-form *S. alterniflora* and *D. spicata*. The authors attribute the increased elevation observed in fertilized plots to this vegetation shift (more turf building), and found that therefore the impact of N enrichment was to allow marshes to accrete at rates outpacing sea level rise.

Rogers J, Harris J and I Valiela. 1998. Interaction of nitrogen supply, sea level rise, and elevation on species form and composition of salt marsh plants. Biological Bulletin (1998): 235-237.

…, data presented here on porewater nitrogen and sulfide concentrations, and supported by previous work (Watson et al. 2014), suggests that high nitrogen loads may fuel the microbially mediated process of organic matter mineralization and sulfate reduction, leading to the decomposition of marsh peat and accumulations of the phytotoxin hydrogen sulfide in marsh soils. While not conclusive, these results suggest it is possible that SLR and high nitrogen loads may synergistically degrade marshes by cooperatively contributing to elevated hydrogen sulfide concentrations (>3 mM; Fig. 4).

Watson EB, Wigand C, Davey EW, Andrews HM, Bishop J and KB Raposa. 2016. Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for Southern New England. Estuaries and Coasts DOI 10.1007/s12237-016-0069-1

INCREASE IN EXTREME CLIMATE EVENTS

**No specific references found, but increased frequency and/or intensity of precipitation events could result in delivery of more (or larger pulses of) nutrients from nonpoint land sources to marshes.

Sedimentation

CURRENT CONDITION

Using radioisotope analysis, Kolker et al. (2010) demonstrated that accretion and mineral deposition rates in physiographically diverse salt marshes on Long Island, NY, USA accelerated at a rate comparable to the rate of global sea level rise acceleration in the twentieth century. This finding is supported by other studies highlighting that moderate increases in inundation and temperatures may increase sediment trapping and plant productivity, allowing marshes to maintain their elevations with higher water levels (Morris et al. 2002; Kirwan and Mudd 2012).

Carey JC, Moran SB, Kelly RP, Kolker AS and RW Fulweiler. 2017. The declining role of organic matter in New England salt marshes. Estuaries and Coasts. 40(3): 626-639.

Examining the relative contribution of organic and inorganic accumulation is important for understanding the drivers of accretion rates in salt marshes (Bricker-Urso et al. 1989; Turner et al. 2002). Sediment availability in coastal systems is one of the main drivers dictating the relative balance of inorganic vs. organic contributions to accretion. Because riverine sediment supplies are limited in New England (Weston 2013) and particularly in Narragansett Bay (Pilson 1985; Nixon et al. 2009), these marshes rely primarily on the net balance between the biological processes of organic matter decomposition and primary production to keep pace with RSLR (Bricker-Urso et al. 1989).

Carey JC, Moran SB, Kelly RP, Kolker AS and RW Fulweiler. 2017. The declining role of organic matter in New England salt marshes. Estuaries and Coasts. 40(3): 626-639.

…, historical adaptation to sea-level rise indicates that the loss of wetlands is not an inevitable outcome of climate change. Although very rapid rates of sea-level rise may drown some marshes regardless of indirect human impacts, numerical models predict that many wetlands will survive in places in which dams and embankments do not restrict sediment transport (Kirwan et al. 2010) 6.

Kirwan, ML and P Megonigal. 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504: 53-60.

On the south side of Cape Cod the conditions for marsh development appear to be less favorable, with many shallow bays remaining as open water. Here the tidal ranges are much smaller, from 1.8 to 4 ft. This limits the area of foreshore on which *S. alterniflora* can grow and reduces the tidal prism so that the size of the inlets and the currents through them are smaller and the supply of sediment to the basins is thus diminished. The result has been that the rate of deposit of sediment has not been sufficient in the face of rising sea level to fill the basins to a level where marsh can develop. Such marsh as was present when sea level was lower has been drowned out as sea level rose, leaving open water over the greater part of the basins.

Redfield AC. 1972. Development of a New England Salt Marsh. Ecological Monographs, Vol. 42(2): 201-237. Available: http://www.jstor.org/stable/1942263

The sensitivity of the site to overwash deposition is dependent on the height and width of the barrier beach as well as distance from the barrier. The relative rarity of overwash deposition preserved at the site (6 deposits in "700 yr) suggests that the height of the barrier beach has not varied substantially from its modern height. The two closest long-term tide gauge records to Succotash Marsh at Newport, Rhode Island, and New London, Connecticut, have recorded storm surge heights more than 1.5 m above mean sea level at least eight times since 1930 and 1938, respectively (NOAA/NOS/CO-OPS, 2000). If the height of the barrier were significantly lower than present, given the high rate of occurrence of storms capable of overtopping a barrier height of &1.5 m above mean sea level, we expect that overwash would likely have occurred much more frequently. Conversely, if the past barrier height was considerably higher than present, overwash would be extremely unlikely to occur.

Donnelly JP, Bryant SS, Butler J, Dowling J, Fan L, Hausmann N, Newby P, Shuman B, Stern J, Westover K and T Webb. 2001. 700 yr sedimentary record of intense hurricane landfalls in southern New England. GSA Bulletin 113(6):714-727.

Marsh elevation change rates varied somewhat among individual SET stations and among coastal regions in RI, but our SET data show that RI salt marshes are generally not keeping pace with either the short- or long-term rate of SLR. Rates from all 24 SET stations were well below the short-term SLR rate, and rates from 21 stations (88%) were also below the long-term SLR rate. Using data from all 24 SETs, RI marshes gained elevation at a mean rate of 1.40 mm yr^{-1}… Short-term accretion rates averaged 1.83 mm yr^{-1} across all 24 stations.

Raposa, KB, Cole Ekberg ML, Burdick DM, Ernst N and SC Adamowicz. 2017. Elevation change and the vulnerability of Rhode Island (USA) salt marshes to sea-level rise. Reg Environ Change 17(2): 389-397.

Even so, the mean RI accretion rate of 1.83 mm yr^{-1} is lower than rates reported for a number of Connecticut, Massachusetts, and New Hampshire salt marshes (Roman et al. 1997; Anisfeld and Hill 2012; Burdick and Peter 2015), which is likely due to a combination of low sediment supplies and a declining contribution from organic matter (Carey et al. 2015b).

Raposa, KB, Cole Ekberg ML, Burdick DM, Ernst N and SC Adamowicz. 2017. Elevation change and the vulnerability of Rhode Island (USA) salt marshes to sea-level rise. Reg Environ Change 17(2): 389-397.

It is likely that historic ditching also contributes to the current inability of RI salt marshes to keep pace with SLR. During the 1930s, mosquito control ditches were excavated in order to drain surface waters that supported mosquito reproduction, but they ultimately had adverse effects on the marshes and marsh-dependent wildlife (Cottam 1938). Unlike creeks, ditches drain marsh peat at depth and result in elevation loss (Wright 2012). Side-casting of excavated material during ditch construction also formed levees that restricted marsh interiors from receiving sediment input (Kennish 2001).

Raposa, KB, Cole Ekberg ML, Burdick DM, Ernst N and SC Adamowicz. 2017. Elevation change and the vulnerability of Rhode Island (USA) salt marshes to sea-level rise. Reg Environ Change 17(2): 389-397.

There does not appear to be any trend in vertical accretion rates down bay and it appears that the low marshes are accreting slightly faster, while the high marsh accretion agrees quite well with sea level rise (Table 1). All of the locations have probably been exposed to the same change in water level but appear to have experienced differences in inorganic and organic sediment supply which may explain the nearly three-fold range in average accretion rates of the low marshes.

Bricker-Urso S, Nixon SW, Cochran JK, Hirschberg DJ and C Hunt. 1989. Accretion rates and sediment accumulation in Rhode Island salt marshes. Estuaries 12:300-317.

Declines in sediment inputs may also be contributing to marsh deterioration in the Northeastern USA (Weston 2014)…., studies of water clarity and sediment transport in the region find declines in sediment inputs and water column suspended sediment concentrations over recent decades (Borkman and Smayda 1996; Weston 2014; C. Wigand, unpublished data). However, suspended sediment concentrations in Narragansett Bay 40 years ago were only on the order of 4 mg L−1 Morton 1972), below levels normally associated with long-term marsh stability (Kirwan et al. 2010). The decline of sediment availability from 'low" to 'very low" undoubtedly exacerbates marsh loss issues, but is unlikely to be the sole driver of coastal wetland fragmentation.

Watson, E.B., C. Wigand, E.W. Davey, H.M. Andrews, J. Bishop and K. B. Raposa. 2016. Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for Southern New England. Estuaries and Coasts DOI 10.1007/s12237-016-0069-1

Stratigraphic sequences that record progradation of marshes across a subtidal basin have traditionally been interpreted as the result of gradual basin infilling during periods of slow sea-level rise (Redfield, 1965; McCormick, 1968). However, our dated stratigraphy points to an abrupt period of marsh growth where rates of marsh expansion increased by about an order of magnitude following settlement (~1000 m2 yr–1 to ~15000 m2 yr–1). …Our experiments suggest that a landscape defined by an expansive platform and intertwining channel network can replace a landscape dominated by open water in <100 yr if suspended sediment concentrations increase by 1–2 orders of magnitude.

Kirwan ML, Murray AB, Donnelly JP and DR Corbett. 2011. Rapid wetland expansion during European settlement and its implication for marsh survival under modern sediment delivery rates. Geology 40(12): 507-510.

INCREASE IN CO_2

The aboveground C3 parameters that influence sediment trapping were each influenced by the treatments (Table 3)…. The net effect on trapping was an increase only under both elevated CO_2 and added N (Elev+N > each of the other treatments, P<0.01).

White KP, Langley JA, Cahoon DR and JP Megonigal. 2012. C3 and C4 Biomass Allocation Responses to Elevated CO2 and Nitrogen: Contrasting Resource Capture Strategies. Estuaries and Coasts, 35(4): 1028-1035. doi:10.1007/s12237-012-9500-4

CHANGE IN SEA LEVEL

Despite rapidly increasing rates of RSLR, we observe no consistent change in salt marsh accretion rates during the past 30 years in the bay. The more mineral-rich marshes had higher accretion rates compared to those with less inorganic matter content (Fig. 6), highlighting the important role of sediment supplies in marsh accretion.

Carey JC, Moran SB, Kelly RP, Kolker AS and RW Fulweiler. 2017. The declining role of organic matter in New England salt marshes. Estuaries and Coasts. 40(3): 626-639.

Elevation gain occurs through biological and physical feedbacks that couple the rate of sea-level rise to the rate of vertical accretion (the increase in soil surface elevation) (Fig 1). In their role as ecosystem engineers, plants set up distinct feedback loops above and below ground. Above ground, mineral sediment settles out of the water column and onto coastal wetland soils during periods of coastal flooding, so that deposition rates are highest in low elevation marshes that are inundated for long periods of time, and lowest in high elevation marshes that are more rarely flooded (Temmerman et al. 2003; Marion et al. 2009).

Kirwan, ML and P Megonigal. 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504: 53-60.

…expansion of channel networks in response to accelerated sea-level rise may deliver more sediment to portions of the platform that were previously sediment deficient (D'Alpaos et al. 2007; Kirwan et al. 2008).

Kirwan, ML and P Megonigal. 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504: 53-60.

…analyses of marsh stability suggest that for southern New England and Long Island salt marshes, threshold sea level rise rates, above which marshes will convert to tidal flats, have already been exceeded (Kirwan et al. 2010; Weston 2014), due to accelerating RSLR (>2 mm y^{-1}; Donnelly et al. 2004) and suspended sediment concentrations at the extreme low boundary for stable salt marsh (e.g. 2 mg L^{-1}; Morton 1972).

Watson EB, Oczkowski AJ, Wigand C, Hanson AR, Davey EW, Crosby SC, Johnson RL and HM Andrews. 2014. Nutrient enrichment and precipitation changes do not enhance resiliency of salt marshes to sea level rise in the Northeastern U.S. Climatic Change 125:501-509. DOI 10.1007/s10584-1189-x

At North Inlet the majority of total marsh area is situated at an elevation that is higher than that which is optimal for primary production and that is dominated by a stunted form of *S. alterniflora* (Fig. 3). This constraint on productivity is an important factor in maintaining elevation because a rise in relative sea level brings about an increase in production and biomass density that will enhance sediment deposition by increasing the efficiency of sediment trapping (Gleason et al. 1979, Leonard and Luther 1995, Yang 1998). This positive effect of the plant community on sediment trapping was demonstrated experimentally at North Inlet (Fig. 4A).

Morris JT, Sundareshwar PV, Nietch CT, Kjerve B and DR Cahoon. 2002. Responses of coastal wetlands to rising sea level. Ecology 83(10): 2869-2877.

Higher sea levels in combination with higher sediment availability have been shown to result in increasing marsh accretion rates in some instances (Morris et al. 2002; Kirwan and Mudd 2012). Thus, the location of Mamacoke Island on the shores of the Thames River could explain why hurricanes, particularly Irene, potentially played a more important a role in Mamacoke Island accretion compared to Barn Island.

Carey JC, Raposa KB, Wigand C and SW Warren. 2017. Contrasting decadal-scale changes in elevation and vegetation in two Long Island Sound salt marshes. Estuaries and Coasts. 40(3):651-661.

INCREASE IN EXTREME CLIMATE EVENTS

Episodic pulses of sediment accumulation during storms may represent an important mechanism for salt marshes to keep pace with sea-level rise, especially to compensate for periods of sediment deficit or when rates of accumulation are less than the rate of sea-level rise as evidenced in the short-term horizon marker results (Table 1).

Roman CT, Peck JA, Allen JR, King JW and PG Appleby. 1997. Accretion of a New England (U.S.A.) salt marsh in response to inlet migration, storms, and sea-level rise. Estuarine, Coastal and Shelf Science 45: 717-727.

Five intense (category 3 or greater) hurricanes occurring in 1635, 1638, 1815, 1869, and 1938 have made landfall on the New England coast since European settlement. Historical records indicate that four of these hurricanes (1635, 1638, 1815, and 1938) and hurricane Carol, a strong category 2 storm in 1954, produced significant storm surges (>3 m) in southern Rhode Island. Storm surges of this magnitude can overtop barrier islands, removing sediments from the beach and nearshore environment and depositing overwash fans across back-barrier marshes, lakes, and lagoons.

Donnelly JP, Bryant SS, Butler J, Dowling J, Fan L, Hausmann N, Newby P, Shuman B, Stern J, Westover K and T Webb. 2001. 700 yr sedimentary record of intense hurricane landfalls in southern New England. GSA Bulletin 113(6):714-727.

Sediment accumulation rates of up to 24 mm year^{-1} were recorded in the immediate vicinity of the inlet during a period that included several major coastal storms, while feldspar sites remote from the inlet had substantially lower rates (trace accumulation to 2.2 mm year^{-1}). During storm-free periods, accumulation rates did not exceed 6·7 mm year^{-1}, but remained quite variable among sites.

Roman CT, Peck JA, Allen JR, King JW and PG Appleby. 1997. Accretion of a New England (U.S.A.) salt marsh in response to inlet migration, storms, and sea-level rise. Estuarine, Coastal and Shelf Science 45: 717-727.

The formation and migration of inlets within the barrier-marsh system can potentially alter the sensitivity to overwash events. The presence of an active inlet nearby would expose the surrounding marsh to high-velocity currents and waves capable of depositing sand and gravel during small storm events and spring tides.

Donnelly JP, Bryant SS, Butler J, Dowling J, Fan L, Hausmann N, Newby P, Shuman B, Stern J, Westover K and T Webb. 2001. 700 yr sedimentary record of intense hurricane landfalls in southern New England. GSA Bulletin 113(6):714-727.

Severe winter storms caused substantial coastal flooding in New England. The strongest winter storms in New England are termed ‘‘nor’easters’’ and intensify over the relatively warm ocean waters along the East Coast of the United States, south of New England. These storms often produce strong northeast winds, hence the name nor’easter. This northeast wind can cause storm surges of magnitudes similar to those resulting from hurricanes, but typically on northeast-facing coastlines.

Donnelly JP, Bryant SS, Butler J, Dowling J, Fan L, Hausmann N, Newby P, Shuman B, Stern J, Westover K and T Webb. 2001. 700 yr sedimentary record of intense hurricane landfalls in southern New England. GSA Bulletin 113(6):714-727.

Storms appear to be a major factor defining shortterm spatial and temporal variability in saltmarsh sedimentation rates (Stumpf, 1983; Cahoon & Reed, 1995). During the sampling period of June 1991 to August 1993 several major storms impacted the northeastern United States (Davis & Dolan, 1994; FitzGerald et al., 1994), resulting in sediment accumulation rates of up to 24 mm year^{-1} in the vicinity of the Nauset Inlet (Table 1). Sedimentation rates were substantially reduced during storm-free periods.

Roman CT, Peck JA, Allen JR, King JW and PG Appleby. 1997. Accretion of a New England (U.S.A.) salt marsh in response to inlet migration, storms, and sea-level rise. Estuarine, Coastal and Shelf Science 45: 717-727.

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Donnelly JP, Bryant SS, Butler J, Dowling J, Fan L, Hausmann N, Newby P, Shuman B, Stern J, Westover K and T Webb. 2001. 700 yr sedimentary record of intense hurricane landfalls in southern New England. GSA Bulletin 113(6):714-727.

Sediment availability at our CT sites may also have been impacted by the occurrence of several major hurricanes which struck the study sites during the study period (Cahoon 2006; Turner et al. 2006, 2007). On August 2011 and October 2012, the northeast coast of the USA experienced Hurricane Irene and Hurricane ("Superstorm") Sandy, respectively. This hurricane activity may be an important contributor to the increase in accretion rates observed at Mamacoke Marsh during the past decade. For example, Orson et al. (1998) found evidence of a large jump in accretion rates at Barn Island following hurricanes Carol and Dianne in the 1950s.

Carey JC, Raposa KB, Wigand C and SW Warren. 2017. Contrasting decadal-scale changes in elevation and vegetation in two Long Island Sound salt marshes. Estuaries and Coasts. 40(3):651-661.

It is interesting that the accretion rate of the lagoonal marsh appears to have been as great or greater than those of the bay marshes despite a very limited sediment supply (except during storms and hurricanes) and a much smaller tidal range. This supports recent observations that episodic deposition can account for inorganic accumulation (Church et al. 1987).

Bricker-Urso S, Nixon SW, Cochran JK, Hirschberg DJ and C Hunt. 1989. Accretion rates and sediment accumulation in Rhode Island salt marshes. Estuaries 12:300-317.

EROSION

Erosion

CURRENT CONDITION

In these regions [Gulf of Mexico, Venice Lagoon and along tributaries of the Chesapeake Bay], which are characterized by low elevations and/or fast rates of relative sea-level rise, increases in the duration of tidal inundation no longer stimulate plant productivity. Rather, progressive inundation reduces organic matter contributions from plants and accelerates erosion, causing a feedback that accelerates the deterioration of coastal wetlands (Morris et al. 2002, Nyman et al. 1993, Fagherazzi et al. 2006).

Kirwan, ML and P Megonigal. 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504: 53-60.

Lithostratigraphic and radiocarbon data from the inland section of Pattagansett River Marsh, Connecticut, show that this sheltered part of the salt marsh underwent significant erosion twice during the past 600 yr, each time followed by rapid and complete infilling of the eroded space with tidal mud and low marsh and high marsh peat. We argue that the erosion cannot be attributed to increases in tidal prism or to lateral migration of tidal channels. The ±2σ age range (A.D. 1390–1470) for the first low marsh growth in the older regressive sequence agrees well with the age range (A.D. 1400–1440) for a hurricane deposit 60 km to the east. The younger regressive sequence is dated with the greatest probability to the period A.D. 1640–1670, i.e., shortly after the hurricanes of A.D. 1635 and 1638.

Van de Plassche O, Erkens G, van Vliet F, Brandsma J, van der Borg K and AFM de Jong. 2006. Salt-marsh erosion associated with hurricane landfall in southern New England in the fifteenth and seventeenth centuries. Geology 34(10): 829-832.

…, marsh extension is faster when sea level is not rising, and a sensitivity analysis of wave energy at marsh boundaries shows that a sea-level rise of 30 cm increases potential erosion by only 50% (Mariotti et al., 2010), so that the order of magnitude of marsh boundary retreat is likely to remain the same.

Fagherazzi S. 2013. The ephemeral life of a salt marsh. Geology 41(8):943–944.

We conclude that coastal vegetation is best suited to modify and control sedimentary dynamics in response to gradual phenomena like sea-level rise or tidal forces (Marani et al. 2007, Donnelly & Bertness 2001), but is less well-suited to resist punctuated disturbances (Kirwan & Murray 2007, Fagherazzi et al 2006) at the seaward margin of salt marshes, specifically breaking waves. In addition, the soil type (Houwing 2000) and geographical setting (French et al. 2000) are the most important factors to consider when comparing erosion rates among sites.

Feagin RA, Lozada-Bernard SM, Ravens TM, Moller I, Yeager KM and AH Baird. 2009. Does vegetation prevent wave erosion of salt marsh edges? Proc Natl Acad Sci USA 106(25):10109–10113.

INCREASE IN TEMPERATURE

Annual ice scouring of the intertidal marsh surface removes most of the remaining marsh grass during the high spring tides in late winter [in Great Bay, NH]. Ice cover and freezing activity in the intertidal salt marsh dislodge portions of the surface peat. Whole sections of marsh with intact intertidal communities are rafted into lower intertidal or subtidal areas that are often too deep for them to survive (Hardwick-Witman 1985). Ice rafted marsh segments that are deposited within the intertidal zone are a potential means of salt marsh propagation within the Great Bay (Hardwick-Witman 1985, 1986).

Short FT and AC Mathieson. 1992. Estuarine Primary Producers. Chapter 7 in FT Short (ed.), The ecology of the Great Bay Estuary, New Hampshire and Maine: an estuarine profile and bibliography. Jackson Estuarine Laboratory, Univ. New Hampshire, Durham, NH. 222 p.

CHANGE IN SEA LEVEL

Erosion of barrier beach systems due to increased storms and SLR threatens back-barrier marshes. Also, when marshes drown, wind-driven waves will erode them. Platform marshes, such as those in the Northeast, are most vulnerable to rapid erosion, as they will drown all at once compared with ramped marshes found elsewhere.

FitzGerald DM, Fenster MS, Argow BA and IV Buynevich. 2008. Coastal impacts due to sea-level rise. Annu. Rev. Earth Planet. Sci. 36: 601-647.

Shoreline erosion is often a function of greater exposure to wind waves resulting from accelerated SLR; previous studies have found that in comparison with other intertidal landforms, marshes have a high sensitivity to wave erosion with SLR due to covariability between elevation and water depth, fetch, and wave-induced bottom shear stresses (Fagherazzi and Wiberg 2009; Mariotti et al. 2010).

Watson EB, Wigand C, Davey EW, Andrews HM, Bishop J and KB Raposa. 2016. Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for Southern New England. Estuaries and Coasts DOI 10.1007/s12237-016-0069-1

INCREASE IN EXTREME CLIMATE EVENTS

See also: FitzGerald et al. 2008 above (in Erosion/Change in Sea Level)

Based on the analysis of two decades of data, we find that violent storms and hurricanes contribute less than 1% to long- term salt marsh erosion rates. In contrast, moderate storms with a return period of 2.5 mo are those causing the most salt marsh deterioration. Therefore, salt marshes seem more susceptible to variations in mean wave energy rather than changes in the extremes.

Leonardi N, Ganju NK and S Fagherazzi. 2016. A linear relationship between wave power and erosion determines salt-marsh resilience to violent storms and hurricanes. Proc Natl Acad Sci USA 113(1):64-68.

Two important observations are behind the linear nature of the relationship. The first observation is that salt marsh erosion continuously occurs, even under low wave energy conditions, suggesting the absence of a critical threshold in wave energy below which no erosion is expected. This result underlines the importance of relatively low wave energy conditions for salt marsh lateral retreat. The second observation is that, as wave energy increases, salt marshes do not respond with a catastrophic collapse (e.g., absence of exponential growth in erosion rates), highlighting the intrinsic endurance of salt marshes against extreme events.

Leonardi N, Ganju NK and S Fagherazzi. 2016. A linear relationship between wave power and erosion determines salt-marsh resilience to violent storms and hurricanes. Proc Natl Acad Sci USA 113(1):64-68.

Environmental Contaminants

CURRENT CONDITION

Climate change may magnify the adverse environmental effects of pollutants, including metals, pesticides, organic material, nutrients, endocrine disruptors, and atmospheric ozone (O_3; Hansen and Hoffman 2001). It also alters temperature, pH, dilution rates, salinity, and other environmental conditions that modify the availability of pollutants, the exposure and sensitivity of species to pollutants, and the transport patterns, uptake, and toxicity of pollutants (Noyes *et al.* 2009).

Staudt A, Leidner AK, Howard J, Brauman KA, Dukes JS, Hansen LJ, Paukert C, Sabo J and LA Solórzano. 2013. The added complications of climate change: understanding and managing biodiversity and ecosystems. Front Ecol Environ 11(9): 494-501.

Statistically-significant decreasing trace element concentrations were found at both Mussel Watch sites. Zinc decreased at Patience Island, while nickel, copper, zinc, silver and lead all decreased at Dyer Island. The organics ΣDiel and ΣBTs have both decreased at Patience Island. However, at Dyer Island there is a statistically significant increase of ΣPCBs and a significant decrease of hexachlorobenzene.

Lauenstien GG and AY Cantillo. 2002. Contaminant trends in US National Estuarine Research Reserves. Silver Spring, MD, NOAA/National Ocean Service/National Centers for Coastal Ocean Science, (NOAA Technical Memorandum NOS NCCOS CCMA, 156)

INCREASE IN CO_2

Elevated atmospheric CO2 generally increases plant productivity and alters nutrient element cycling, but whether CO2 causes similar effects on the cycling of contaminant elements is unknown. Here we show that 11 years of experimental CO2 enrichment in a sandy soil with low organic matter content causes plants to accumulate contaminants in plant biomass, with declines in the extractable contaminant element pools in surface soils. These results indicate that CO2 alters the distribution of contaminant elements in ecosystems, with plant element accumulation and declining soil availability both likely explained by the CO2 stimulation of plant biomass. Our results highlight the interdependence of element cycles and the importance of taking a broad view of the periodic table when the effects of global environmental change on ecosystem biogeochemistry are considered.

Duval BD, Dijkstra P, Natali SM, Megonigal JP, Ketterer ME, Drake BG, Lerdau MT, Gordon G, Anbar AD and BA Hungate. 2011. Plant-soil distribution of potentially toxic elements in response to elevated atmospheric CO2. Environmental Science and Technology. 45: 2570-2574

INCREASE IN TEMPERATURE

Higher temperatures can also exacerbate hypoxic conditions because warmer water holds less dissolved oxygen than cooler water and accelerates the bacterial decay of organic matter, which in turn consumes more oxygen (Rabalais *et al.* 2009). More frequent extreme rainfall events can further exacerbate hypoxia by increasing the runoff of nitrogen and phosphorus (P) into waterways.

Staudt A, Leidner AK, Howard J, Brauman KA, Dukes JS, Hansen LJ, Paukert C, Sabo J and LA Solórzano. 2013. The added complications of climate change: understanding and managing biodiversity and ecosystems. Front Ecol Environ 11(9): 494-501.

Increases in temperature will enhance the toxicity of contaminants and increase concentrations of tropospheric ozone regionally, but will also likely increase rates of chemical degradation.

**Noyes PD, McElwee MK, Miller HD, Clark BW, Van Tiem LA, Walcott KC, Erwin KN and ED Levin. 2009. The toxicology of climate change: environmental contaminants in a warming world. Environmental International. 35:
971-986.**

Temperature-induced acceleration of organic carbon metabolism by soil and sediment biota could also increase contaminant concentrations and promote partitioning to water and aquatic biota… Increased temperature will also increase volatilization of POPs from soils to air where they will be subject to photodegradation and transport… Migratory species, particularly fish, birds, and marine mammals, may be exposed to contaminants in one location and transport these contaminants in substantial quantities to other locations. This biotic transport of contaminants may be similar in magnitude to atmospheric and oceanic transport.

**Noyes PD, McElwee MK, Miller HD, Clark BW, Van Tiem LA, Walcott KC, Erwin KN and ED Levin. 2009. The toxicology of climate change: environmental contaminants in a warming world. Environmental International. 35:
971-986.**

The bioavailability and toxicity of POPs and pesticides in wildlife is likely to increase in response to rising temperature and salinity. An underlying mechanism of this interactive toxicity is that increasing temperature can alter homeostasis and other key physiological mechanisms, thereby exacerbating the adverse effects of contaminants. Moreover, the rapidity of climate change-induced shifts in habitats and trophic food webs could affect contaminant toxicity by altering exposure pathways and increasing susceptibility of some populations, especially those already under stress.

**Noyes PD, McElwee MK, Miller HD, Clark BW, Van Tiem LA, Walcott KC, Erwin KN and ED Levin. 2009. The toxicology of climate change: environmental contaminants in a warming world. Environmental International. 35:
971-986.**

Rising temperatures, for instance, can enhance exposure to metals by increasing the respiration rates of fish.

Staudt A, Leidner AK, Howard J, Brauman KA, Dukes JS, Hansen LJ, Paukert C, Sabo J and LA Solórzano. 2013. The added complications of climate change: understanding and managing biodiversity and ecosystems. Front Ecol Environ 11(9): 494-501.

CHANGE IN PRECIPITATION

Climate change-induced shifts in precipitation patterns will also affect PM (particulate matter) fate and behavior.

Noyes PD, McElwee MK, Miller HD, Clark BW, Van Tiem LA, Walcott KC, Erwin KN and ED Levin. 2009. The toxicology of climate change: environmental contaminants in a warming world. Environmental International. 35:
971-986.

As storms and rainfall events become more intense and frequent, increasing amounts of contaminants will be deposited to surfaces and lost in runoff, predominantly as pulse releases, exposing humans and wildlife to these chemicals.

Noyes PD, McElwee MK, Miller HD, Clark BW, Van Tiem LA, Walcott KC, Erwin KN and ED Levin. 2009. The toxicology of climate change: environmental contaminants in a warming world. Environmental International. 35:
971-986.

For example, a recent meta-analysis of empirical studies found that biodiversity was more likely to be negatively affected by habitat loss in areas where precipitation rates have changed.

Staudt A, Leidner AK, Howard J, Brauman KA, Dukes JS, Hansen LJ, Paukert C, Sabo J and LA Solórzano. 2013. The added complications of climate change: understanding and managing biodiversity and ecosystems. Front Ecol Environ 11(9): 494-501.

Rising temperatures, for instance, can enhance exposure to metals by increasing the respiration rates of fish.

Staudt A, Leidner AK, Howard J, Brauman KA, Dukes JS, Hansen LJ, Paukert C, Sabo J and LA Solórzano. 2013. The added complications of climate change: understanding and managing biodiversity and ecosystems. Front Ecol Environ 11(9): 494-501.

CHANGE IN SEA LEVEL

See also Land use / Land cover maps if available (note adjacent land use and potential for increased contaminants associated with coastal flooding)

Sea level rise linked to climate change is projected to lead to salt water intrusion into previously freshwater habitats. However, salinity could decrease in waters receiving elevated inputs of freshwater due to increases in precipitation or snow and ice melt. In sun, the effects of climate change on salinity patters are complex and may vary by region as a number of factors can influence this parameter… Salinity interactions are made additionally complex because salinity can influence the chemical itself or it may modulate toxicity and physiological functioning of species… Thus increased contaminant bioavailability and toxicity is possible in subtropical latitudes experience increased salinity, as well as in estuaries and coastal freshwater ecosystems subject to increased saltwater intrusions or droughts.

Noyes PD, McElwee MK, Miller HD, Clark BW, Van Tiem LA, Walcott KC, Erwin KN and ED Levin. 2009. The toxicology of climate change: environmental contaminants in a warming world. Environmental International. 35:
971-986.

ENVIRONMENTAL CONTAMINANTS

INCREASE IN EXTREME CLIMATE EVENTS

See also STORMTOOLS – an on-line tool for homeowners and municipalities to understand how sea level rise will affect their properties/communities

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Noyes PD, McElwee MK, Miller HD, Clark BW, Van Tiem LA, Walcott KC, Erwin KN and ED Levin. 2009. The toxicology of climate change: environmental contaminants in a warming world. Environmental International. 35: 971-986.

Perhaps one of the simplest ways in which increased storm intensity or frequency can interact with contaminants is through the re-entry of sediment-bound contaminants and pathogens into nearshore ecosystems in the wake of such storms. Effects on shallow-water sediments are intrinsically linked with biota.

Schiedek D, Sundelin B, Readman JW and RW Macdonald. 2007. Interactions between climate change and contaminants. Marine Pollution Bulletin. 54: 1845-1856.

Adaptive Capacity

DEGREE OF FRAGMENTATION

See also TNC's Resilient Land Mapping Tool
SHARP (Elphick et al.) (http://www.tidalmarshbirds.org/)

Within the Northeastern U.S. and Maritime Canada, geological diversity, elevation range and latitude appear to drive regional species diversity patterns more so than climate, with the most predictive of species diversity of all combinations of
23 geophysical and climatic variables being (1) the number of geological classes, (2) latitude, (3) elevation range and (4) the amount of calcareous bedrock (certainty (adj. R2 = 0.94)). It follows that spatial pattern of total biodiversity will likely remain associated with these enduring geophysical features even as individual species ranges shift with climate change. Conserving geophysical settings may offer a conservation approach that protects diversity under both current and future climates.

Anderson MG and CE Ferree. 2010. Conserving the stage: Climate change and the geophysical underpinnings of species diversity. PLoS ONE 5(7): e11554.doi:10.1371/journal.pone.0011554

Metrics developed for estimating site resilience combine measures of sites' physical complexities (landform variety, elevation range, and wetland density) as well as permeability (local connectedness and regional flow patterns). The results sections (Chapters 5 and 6) as well as TNC's Resilient Land Mapping Tool) identify the network of sites with the highest estimated resilience within each ecological region.

Anderson MG, Clark M and AO Sheldon. 2012. Resilient sites for terrestrial conservation in the Northeast and Mid-Atlantic Region. The Nature Conservancy, Eastern Conservation Science. 168 pp.

Expanded on previous work, within each geophysical setting, identified sites that were both connected by natural cover and that had relatively more microclimates indicated by diverse topography and elevation gradients. Site resilience scores were a combination of landscape diversity (variety of landforms, elevation range, and wetland density) and local connectedness (landscape permeability). Low and coastal elevations, as well as alkaline and more erodible settings (calcareous, coarse sand, fine silt) had the lowest estimated resilience; acidic and resistant bedrock settings (granite, mafic, acidic sedimentary) had the highest. These patterns were reflected in the separate landscape diversity and local connectedness scores and in the combined index, indicating that landscapes in the latter geologies were both flatter and more fragmented. Estimated resilience scores decreased consistently as elevation decreased.

Anderson MG, Clark M and AO Sheldon. 2014. Estimating climate resilience for conservation across geophysical settings. Conserv Biol. 28: 959–970. doi:10.1111/cobi.12272

When compared to TNC sites selected for their high-quality rare species populations and natural community occurrence, high-scoring sites captured significantly more of the biodiversity sites than expected by chance ($p < 0.0001$). Average scores for TNC's sites were calculated by taxa and by community, and the marshes scores were as follows: (scores are mean of the z scores in units of SD: landscape diversity (0.05), local connectedness (0.02), and resilience (0.07).

Anderson MG, Clark M and AO Sheldon. 2014. Estimating climate resilience for conservation across geophysical settings. Conserv Biol. 28: 959–970. doi:10.1111/cobi.12272

Note: Site resilience measures were based on geophysical sites (40–4000 ha), which are larger than all but a couple of (intact) RI salt marsh systems.
Due to data limitations, the RI team didn't address SLR or past land uses that might have altered geophysical structure.

BARRIERS TO MIGRATION

For all coastlines in the northeast:

See also LIDAR-2011 1m resolution LiDAR and bare earth Digital Elevation Model (available on RIGIS) attained as part of the LiDAR for the Northeast project in partnership with USGS

For Rhode Island:

See also SLAMM-Sea Level Affecting Marshes Model run by TNC for CRMC (contact: Kevin Ruddock) highlights barriers to marsh migration for multiple sea level rise scenarios (1, 3 and 5 feet by 2100) using 2003-04 Land Use Land Cover data from RIGIS, 2010 National Wetlands Inventory maps and 2011 LiDAR elevation data (maps and report available here: www.crmc.ri.gov/maps/maps_slamm.html)

See also RIGIS hardened shorelines-2003 dataset developed by the Narragansett Bay National Estuary Program, available on RIGIS

Seawalls eliminated the vegetative transition zone at the upper border. Not only did the plant community of the transition zone have high plant diversity relative to the low marsh, but it varied greatly from site to site in the estuary. The effects of seawall presence on other marsh processes, including sediment movement, wrack accumulation, groundwater flow, and vegetation distribution and growth, were examined. Although no statistically significant effects of seawalls were found, variation in the indicators of these processes were largely controlled by wave exposure, site-specific geomorphology and land use, and distance of the sampling station from the upland. Trends indicated there was more sediment movement close to seawalls at high energy sites and less fine grain sediment near seawalls.

Bozek CM and DM Burdick. 2005. Impacts of seawalls on saltmarsh plant communities in the Great Bay Estuary, New Hampshire USA. Wetlands Ecology and Management 13: 553–568.

Losses in ecosystem services from submerged tidal wetlands can be mitigated by allowing the high marsh to migrate into adjacent uplands and non-tidal wetlands. Barriers will need to be removed and provision for tidal waters and suspended sediments to nourish the marshes will be needed, specifically for large culverts and bridges where transportation paths cross wetlands. Losses of tidal wetlands in highly developed areas are unlikely to be replaced by migration, so extra planning efforts and negotiations need to be made on less developed and protected lands to ensure these critical habitats can be maintained.

City of Portsmouth Planning Department. 2013. City of Portsmouth, New Hampshire, coastal resilience initiative. City of Portsmouth, NH. 85 p.

A simple (cheap, easy to replicate, doesn't require extensive specialized knowledge) protocol to generate baseline data for long-term monitoring of marsh migration along the Long Island Sound coast focused on 3 questions: (1) is the marsh moving inland (measuring how far saltmarsh plants encroach terrestrial habitat, (2) are terrestrial plants being affected by saltwater encroachment (documenting evidence for elevated tree mortality at the marsh edge; and (3) is the fauna changing (describing the bird community). This protocol can be extended to other regions with little modification.

Elphick CS and CR Field. 2014. Monitoring indicators of climate change along long Island Sound: A simple protocol for collecting baseline data on marsh migration. Wetland Science and Practice 31:7-9.

RECOVERY / REGENERATION FOLLOWING DISTURBANCE

Several winter rainstorms deposited a large amount of virgin sediment… The establishment of a new marsh community was followed at this site from 1987 to 1991. Seedling survival was relatively low with only 5% surviving for a year or longer. Seedlings which did become successfully established rapidly by expanded vegetative growth. *Salicornia virginica*, *Frankenia grandifolia* and *Distichlis spicata* were the most successful species occupying at least 20% cover across most of the study area, bat other species became established as well. Seedling survival and plant establishment were greatest in following heavy spring rains which provided large inputs of fresh water. Disturbances followed by conditions that lower stress, which would otherwise prevent germination and growth, are important for the rapid establishment of a marsh.

Allison, SK. 1996. Recruitment and establishment of salt marsh plants following disturbance by flooding. The American Midland Naturalist. 136(2):232-247. DOI: 10.2307/2426728

Beginning in the 17th century many Bay of Fundy marshes were diked and drained for agricultural use, but storm breaching of dikes and failure of tidal gates has returned tidal flooding to some marshes. Comparisons of reference and recovering diked marshes inform not only restoration activities on the Bay of Fundy, but also give a perspective on recovery trajectories of reclaimed salt marshes in general.

Byers SE and GL Chmura. 2007. Salt marsh vegetation recovery on the Bay of Fundy. Estuaries and Coasts 30(5): 869–877.

When selecting suitable sites for restoration, one must consider physical, biological, logistical and historical criteria. Spatial arrangement of restored patches, their size and distance from one another are equally important considerations. Practitioners can choose the largest patches in the best available habitat for reintroducing target species.

Fiedler PL and RD Laven. 1996. Selecting reintroduction sites. In: Falk, D.A., Millar, C.I., Olwell, M., eds. Restoring Diversity: Strategies for Reintroduction of Endangered Plants. Washington, DC. Island Press: 157-169.

Ecological restoration of degraded land is included in the array of potential human responses to climate change. However, the implications of climate change for the broader practice of ecological restoration must be considered. In particular, the usefulness of historical ecosystem conditions as targets and references must be set against the likelihood that restoring these historic ecosystems is unlikely to be easy, or even possible, in the changed biophysical conditions of the future. The authors suggest that more consideration and debate needs to be directed at the implications of climate change for restoration practice.

Harris JA, Hobbs RJ, Higgs E and J Aronson. 2006. Ecological restoration and global climate change. Restoration Ecology. 14(2): 170-176.

Oil spills represent a major environmental threat to coastal wetlands, which provide a variety of critical ecosystem services to humanity. Following the BP Deepwater Horizon oil spill, we sampled the terrestrial arthropod community and marine invertebrates found in stands of *Spartina alterniflora*, the most abundant plant in coastal salt marshes. Intertidal crabs and terrestrial arthropods (insects and spiders) were suppressed by oil exposure even in seemingly unaffected stands of plants; however, *Littoraria* snails were unaffected. One year later, crab and arthropods had largely recovered. Our work is the first attempt that we know of assessing vulnerability of the salt marsh arthropod community to oil exposure, and it suggests that arthropods are both quite vulnerable to oil exposure and quite resilient, able to recover from exposure within a year if host plants remain healthy.

McCall BD and SC Pennings. 2012. Disturbance and recovery of salt marsh arthropod communities following BP Deepwater Horizon oil spill. PLoS ONE 7(3): e32735. doi:10.1371/journal.pone.0032735

Our study reports that vegetated area in RI backbarrier marshes expanded during the first part of the twentieth century, but declined during the last decades of the twentieth century, resulting in marsh vegetation loss since the 1970s for all but one of the backbarrier marshes studied. Closer examination of barrier features suggests that this pattern is linked to widening of inlets. Where tidal exchange occurs through narrow inlets that traverse coastal barriers, the effective tidal range experienced in a geographic unit can be quite restricted compared with that of adjacent ocean, sound, estuary, or bay. Backbarrier marshes are thus responding to changes in inundation that are related to SLR, but can be buffered or amplified by changes in inlet dimension, which ultimately determine inundation patterns.

Watson, E.B., C. Wigand, E.W. Davey, H.M. Andrews, J. Bishop and K. B. Raposa. 2016. Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for Southern New England. Estuaries and Coasts DOI 10.1007/s12237-016-0069-1

Backbarrier estuaries are very sensitive to changes in inlet dimension, the sensitivity of which has important implications for regional marsh stability. Where a backbarrier marsh is low in elevation, inlet widening from increased storm frequency may lead to dramatic increases in inundation that far exceed high rates of SLR, due to the rapid increase in tidal range.

Watson, E.B., C. Wigand, E.W. Davey, H.M. Andrews, J. Bishop and K. B. Raposa. 2016. Wetland loss patterns and inundation-productivity relationships prognosticate widespread salt marsh loss for Southern New England. Estuaries and Coasts DOI 10.1007/s12237-016-0069-1

Due to the character of salt marsh and seagrass habitats, human-induced losses may be very slow to recover. In fact, in many cases reestablishment of these habitats is not possible without active human intervention through restoration efforts (Kusler and Kentula 1990).

Short FT, Jones SH, Sale PF and T Wellenberger. 1992. Great Bay Estuary management issues. Chapter 10 in F.T. Short (ed.) The ecology of the Great Bay Estuary, New Hampshire and Maine: an estuarine profile and bibliography. Jackson Estuarine Laboratory, Univ. New Hampshire, Durham, NH. 222 p.

DIVERSITY OF FUNCTIONAL GROUPS

Frequency, intensity, extent and locations of disturbance will affect whether, how and at which rate the existing ecosystems will be replaced by new plant and animal assemblages. The impact of sea-level rise on coastal ecosystems will vary regionally and will depend on erosion processes from the sea and depositional processes from land. The risk of extinction will increase for many species that are already vulnerable. Where there is a loss of dominant species or a high proportion of species redundancy, there may be losses in net ecosystem productivity.

Gitay H, Suarez A, Watson RT and DJ Dokken. 2002. Climate change and biodiversity. Geneva, Switzerland: Intergovernmental Panel on Climate Change. 85 pp.

Community similarity is thought to decay with distance. No studies have explicitly examined variation in salt marsh plant community composition across geographical scales, and from species, functional and phylogenetic perspectives. We hypothesized that community turnover would be more rapid at local versus larger geographical scales; and that community turnover patterns would diverge among compositional perspectives, with a greater distance decay at the species level than at the functional or phylogenetic levels. There was strong variation in community composition within individual salt marsh sites across elevation; in contrast, community similarity decayed with distance more slowly across sites within each region. Local gradients are relatively more important than regional processes in structuring coastal salt marsh communities. In ecosystems with low species diversity, functional and phylogenetic approaches may not provide additional insight over a species-based approach.

Guo H, Chamberlain SA, Elhaik E, Jalli I, Lynes A-R, Marczak L, Sabath N, Vargas A, Wieski K, Zelig EM, Pennings SC and B Li. 2015. Geographic variation in plant community structure of salt marshes: Species, functional and phylogenetic perspectives. PLoS ONE 10(5): e0127781. doi:10.1371/journal.pone.0127781

Climate change creates new challenges for biodiversity conservation. Species ranges and ecological dynamics are already responding to recent climate shifts, and current reserves will not continue to support all species they were designed to protect. These problems are exacerbated by other global changes. Several consistent recommendations emerge for action at diverse spatial scales. Broadly, adaptation requires improved regional institutional coordination, expanded spatial and temporal perspective, incorporation of climate change scenarios into all planning and action, and greater effort to address multiple threats and global change drivers simultaneously in ways that are responsive to and inclusive of human communities. need for (1) more specific, operational examples of adaptation principles that are consistent with unavoidable uncertainty about the future; (2) a practical adaptation planning process to guide selection and integration of recommendations into existing policies and programs; and (3) greater integration of social science into an endeavor that, although dominated by ecology, increasingly recommends extension beyond reserves and into human-occupied landscapes.

Heller NE and ES Zavaleta. 2009. Biodiversity management in the face of climate change: a review of 22 years of recommendations. Biological Conservation. 142(1): 14-32.

Given the key role of climate in determining the distribution and abundance of organisms, climate change has the potential to inflict major impacts on Massachusetts' biological communities and species. Indeed, we are already seeing clear climate change impacts on ecosystems and species in North America and elsewhere.

Temperature extremes are of particular importance for wildlife. The growing season, the number of days between last and first frost, is projected to lengthen.

Manomet Center for Conservation Sciences. 2010. Climate change and Massachusetts fish and wildlife: volume 1. Brunswick, ME: Manomet Center for Conservation Sciences. 19 pp.

Evidence from paleoclimatological research indicates that major climatic changes can occur over the span of a few decades. Vegetation response to climatic variation and change, is, by contrast, often assumed to occur gradually over much longer timescales. Two recent papers confirm earlier, theoretical predictions that changes in species composition of plant communities following climatic shifts can, however, occur with striking rapidity.

Post E . 2003. Climate-vegetation dynamics in the fast lane. Trends in Ecology and Evolution. 18(11): 551-553.

Knowing that diverse plantings enhanced biomass and nitrogen accumulation in a restored California salt marsh, we asked if the ''biodiversity effect'' was due to species selection or complementarity. In a two-year greenhouse experiment, we found positive biodiversity effects on total, root, and shoot biomass, total and root N crop, and on biomass and N allocation; negative effects on root and shoot N concentration; and no effect on shoot N crop. When we decomposed biodiversity effects on shoot characteristics, selection effects primarily drove over- and underyielding. One species (*Salicornia virginica*) dominated functioning when present; when absent, another dominated. Evidence for strong species selection effects led us to predict that three species would eventually dominate our parallel field experiment that tested the same assemblages. Exactly that happened in nine years, but (we predict) without losing function, because the site retained the three highest-performing species. Biodiversity loss was nonrandom in the field and we predict that many functions will not decline, even if the salt marsh becomes dominated by a single species.

Sullivan G, Callaway JC and JB Zedler. 2007. Plant assemblage composition explains and predicts how biodiversity affects salt marsh functioning. Ecological Monographs 77:569–590.

MANAGEMENT ACTIONS

An evaluation of the global distribution and extent of human impacts on the structure and function of coastal salt marshes. Of the various impacts, invasive species, runaway consumer effects, and sea level rise represent the greatest threats to salt marsh ecosystems. We conclude that the best way to protect salt marshes and the services they provide is through the integrated approach of ecosystem-based management.

Gedan KB, Silliman BR and MD Bertness. 2009. Centuries of human-driven change in salt marsh ecosystems. Annual Review of Marine Science 1: 117-141.

The strategy outlined selection criteria for marshes in an adjacent to Blackwater Wildlife Refuge where management actions would likely yield the greatest long-term conservation benefits. Criteria include greatest predicted longevity under sea level rise scenarios, most intact current condition defined by lack of interior ponding, highest abundance of focal salt marsh birds measured by SHARP surveys and extensive area of contiguous interior. Recommended marsh management techniques include using sediment enhancement, reduction of interior ponding and control of invasive plants. Marsh corridors to conserve were identified using SLAMM Strategies for managing the transition of uplands into marsh were outlined including *Phragmites* control, removal of dead trees and planting transition crops of native, salt-tolerant grasses.

Lerner JA, Curson DR, Whitbeck M and EJ Meyers. 2013. Blackwater 2100: A strategy for salt marsh persistence in an era of climate change. The Conservation Fund (Arlington, VA) and Audubon MD-DC (Baltimore, MD).

If some expansive marshes are indeed a relict feature of historical land-use change, could widespread degradation observed today represent a slow return of marshes to their low sediment supply, pre-settlement extent? This transition would involve an enormous loss in ecosystem services, and raises an interesting paradox for managers and policy makers. Our results suggest that expensive wetland restoration may in some cases amount to an attempt to prevent coastal wetlands from returning to their natural state.

Kirwan ML, Murray AB, Donnelly JP and DR Corbett. 2011. Rapid wetland expansion during European settlement and its implication for marsh survival under modern sediment delivery rates. Geology 40(12): 507-510.

The study found that there are 50 locations where non-natural restrictions impact the daily flux of the tide, which is the lifeblood of a healthy salt marsh ecosystem. These restrictions, many of which have been in place for years, affect over 1,300 acres, 20 percent of the total remaining salt marshes in New Hampshire. Such restrictions are detrimental to the quality of this valuable resource. Of the 50 restrictions, 45 are located along the Atlantic Coast and impact approximately 1,214 acres (93 percent of the total) while five, affecting about 98 acres, are located along the Piscataqua River or within the Great/Little Bay estuary. Hampton and Rye contain the largest number of restrictions and affected acreages.

USDA Natural Resources Conservation Service. 2001 (Reissued). Evaluation of restorable salt marshes in New Hampshire. USDA, NRCS. 43 p.

Our results show that salt marshes have value for coastal hazard mitigation and climate change adaptation. Because we do not yet fully understand the magnitude of this value, we propose that decision makers employ natural systems to maximize the benefits and ecosystem services provided by salt marshes and exercise caution when making decisions that erode these services.

Shepard CC, Crain CM and MW Beck. 2011. The protective role of coastal marshes: A systematic review and meta-analysis. PLoS ONE 6(11): e27374. doi:10.1371/journal.pone.0027374. 11 p.

Although tidal-flow restorations in Connecticut control *Phragmites australis* and restore native saltmarsh vegetation, they produce conditions that are largely unsuitable for one of the highest conservation priority species found in eastern US salt marshes- saltmarsh sparrow. Bird communities in 21 plots in restoration sites and 19 plots reference sites were examined. Restoration plots were divided into those where management involved restoring tidal flow and those that involved direct *Phragmites* control (e.g. cutting, herbicide). Saltmarsh sparrows were less common where tidal flow had been restored than at reference sites and nested in only one of the 14 tidal-flow restoration plots. No abundance differences were found for large wading birds, willets, or seaside sparrows. Vegetation at sites where tidal flow had been restore showed characteristics typical of lower-elevation marsh, which is unsuitable for nesting saltmarsh sparrows.

Elphick CS, Meiman S and MA Rubega. 2015. Tidal-flow restoration provides little nesting habitat for a globally vulnerable saltmarsh bird. Restoration Ecology 23:439–446.

INSTITUTIONAL / HUMAN RESPONSE

See also Bertness MD, Brisson CP and SM Crotty. 2015. Indirect anthropogenic effects turn off reciprocal feedbacks and decrease resilience in a New England salt marsh. Oecologia 178(1): 231-237.

Sea level rise will inundate marshlands, which act as a buffer against waves, filter pollutants, and provide irreplaceable habitat for wildlife. New England's marshlands act as nurseries for commercially important species such as lobsters, clams, scallops and herring, and they provide hunting grounds for bluefish and striped bass.62 In Massachusetts alone, the combined value of these marsh-dependent fish topped $400 million in 2011.63

Natural Resources Committee Democrats. 2012. How climate change jeopardizes the Northeast's economy and environment. E. Markey, Chair. October 25, 2012. 15 p.

Shoreline hardening is recognized to reduce ecosystem services that coastal populations rely on, but the amount of hardened coastline continues to grow in many ecologically important coastal regions. Therefore, to inform future management decisions, we conducted a meta-analysis of studies comparing the ecosystem services of biodiversity (richness or diversity) and habitat provisioning (organism abundance) along shorelines with versus without engineered-shore structures. Seawalls supported 23% lower biodiversity and 45% fewer organisms than natural shorelines.

Gittman RK, Scyphers SB, Smith CS, Neylan IP and JH Grabowski. 2016. Ecological consequences of shoreline hardening: A meta-analysis. BioScience 66(9):763-773.

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