SURFACE ELEVATION TRENDS IN NORTH CAROLINA'S COASTAL WETLANDS

A White Paper by the North Carolina SET Community of Practice

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Coastal wetlands exist in the narrow fringe between uplands and open water and consequently, are uniquely vulnerable to the impacts of sea level rise (SLR). Predictive models suggest that in the coming decades sea level rise will lead to substantial losses of coastal wetland habitat in North Carolina. Empirical measurements of wetland response to SLR are vital for understanding which wetland complexes are most immediately threatened, so that mitigation, adaptation, and conservation efforts can be prioritized accordingly. Surface Elevation Tables (SETs) provide high resolution measures of wetland elevation change that can meet this need.

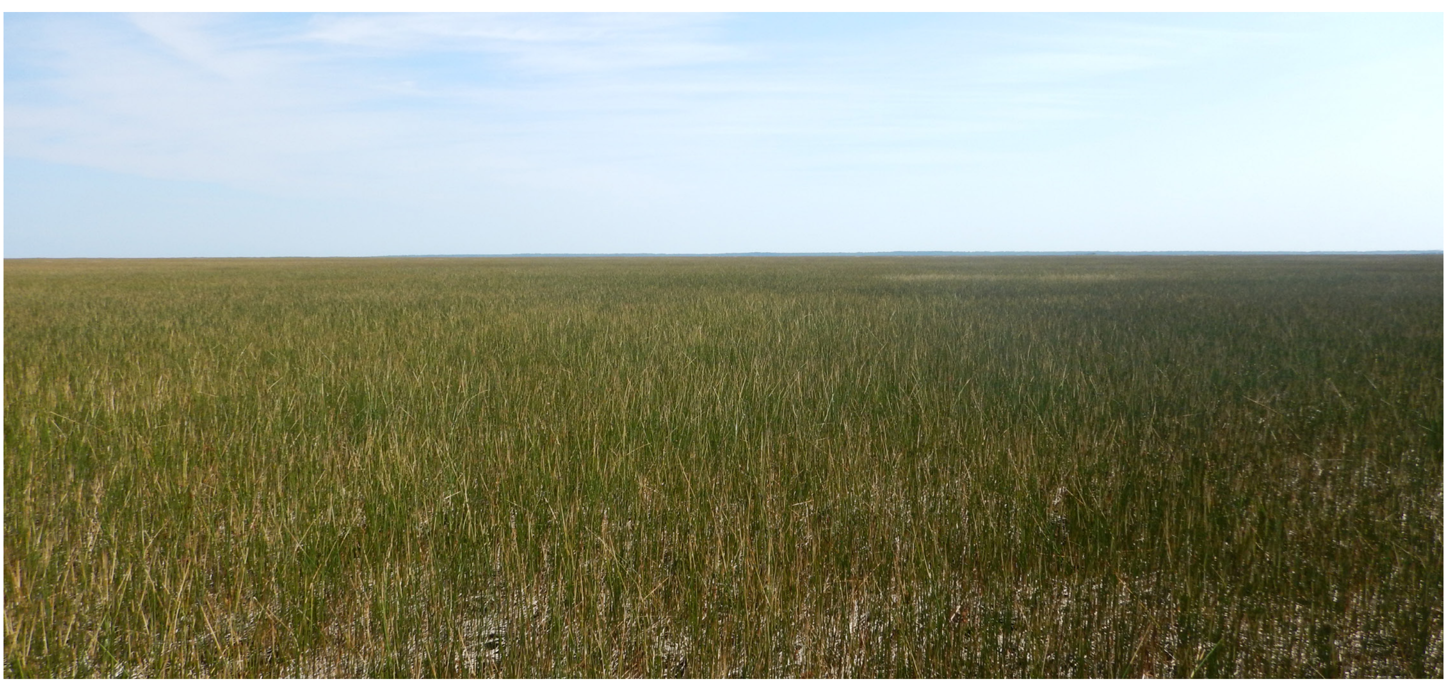
The North Carolina SET Community of Practice (NC SET COP) is a voluntary and unfunded partnership among stakeholders who have either installed Surface Elevation Tables (SETs) in North Carolina coastal wetlands, or who rely on SET data. The NC SET COP was formed in 2018 to identify and map the locations of all SETs installed within North Carolina, increase collaboration among SET users, and support efforts to identify regional trends in North Carolina coastal wetland response to sea level rise. The data presented here represent the first synoptic analysis of elevation trend data collected by NC SET COP partners.

Of 132 SETs installed across North Carolina (NC), 33 recorded net losses in elevation over the entire record of measurement. Among the 99 SETs that recorded positive elevation change, 79 (80%) did not build elevation fast enough to keep pace with the average rate of SLR over the past 30 years. The story these data tell is clear: the majority of NC's coastal wetlands are not keeping pace with SLR. These data also provide a spatially explicit understanding of which wetlands are most at risk, and as a result, the SET data can help guide the use of restoration efforts for maximum effectiveness.

INTRODUCTION

The future of coastal wetlands is uncertain. Coastal wetlands protect communities by buffering the energy of storms, improving water quality in bays and estuaries, supplying nutrients to marine food webs, providing critical habitat for birds and wildlife, and acting as nurseries for many commercially important species of fish and shellfish (Daily et al. 1997; Barbier et al. 2011). The plant communities that inhabit coastal wetlands are uniquely adapted to life in water-logged soils. In most cases, these plants are tolerant of being inundated with water for prolonged intervals but cannot survive constant inundation. When sea level increases relative to wetland surface elevation, so does the amount of time that wetland plants spend inundated. As a result, the future abundance and distribution of wetlands will be strongly influenced by changes in sea level. Coastal wetlands exist along a range of salinities, from freshwater (forested wetlands) to full strength seawater (salt marshes). As sea levels rise, salinities increase further inland, further altering plant communities.

Rates of sea level rise (SLR) are increasing globally. From 1901 to 1971, the average global rate of SLR was 1.3 mm yr^{-1}, but from 2006 to 2018 it accelerated to 3.7 mm yr^{-1} (IPCC 2023). However, these rates are not uniform across the globe, with some areas experiencing higher or lower rates (Sweet et al. 2022). In the past 15 years, the US Southeast and Gulf Coasts have experienced rates of SLR up to three times higher than the global average due to changes in ocean circulation (Dagendorf et al. 2023). Annual increases on the order of 5-10 mm yr^{-1} have been reported for the North Carolina coast in recent decades (Hilting et al. 2021, Valle-Levinson et al. 2017). Predictions suggest that SLR will continue to accelerate over coming decades (Sweet et al. 2022), and mounting evidence suggests that North Carolina's coastal wetlands are unlikely to keep pace (Warnell et al. 2022, Familkhalili et al. 2023, Moorman et al. 2023). Further, land subsidence along much of coastal North Carolina is exacerbating the effects of SLR. In general, subsidence rates tend to increase from south to north along the coast of North Carolina, with rates at Southport estimated at -0.51 mm yr^{-1} and rates at Duck estimated at -1.49 mm yr^{-1} (North Carolina Coastal Resources Commission, 2015). The highest reported subsidence rates in North Carolina are near Swan Quarter (c. -2.5 mm yr^{-1}; Kareger et al. 2016; Johnston et al. 2021). Subsidence is largely a function of global factors like tectonic structure and glacial isostatic adjustment, however some human-caused drivers can contribute to more localized subsidence. Key contributors include groundwater extraction (Galloway et al. 2011), the construction of dams and other infrastructure that block the natural flow of



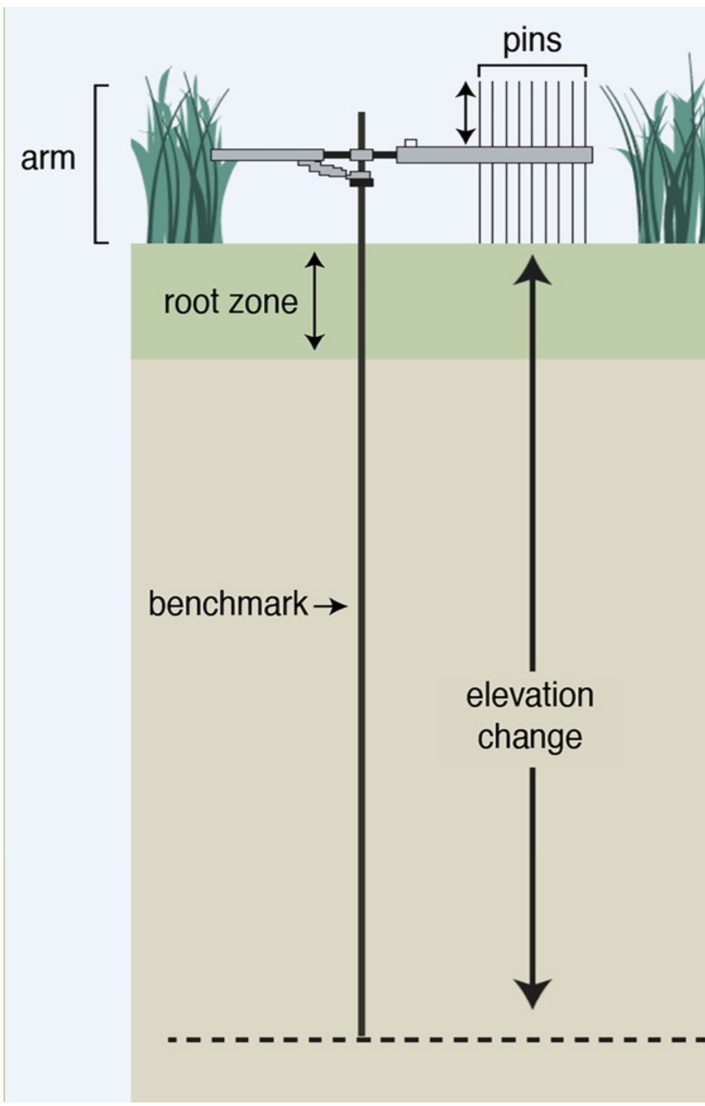
sediment that would otherwise travel down rivers and replenish coastal lands, and the drying and compaction of peat soils (Keogh et al. 2021). The combination of SLR and subsidence is referred to as relative SLR. In this document, we use the term SLR to refer to increases in water elevation relative to that of land elevation regardless of the cause.

Over two million acres of wetlands are present in North Carolina's coastal counties (NOAA 2016). For these wetlands to persist in the face of rising relative sea levels they must either maintain an elevation that is commensurate with vegetation tolerances for frequency and duration of flooding, or migrate inland to higher elevations (Brinson et al. 1995). Landward migration will occur naturally in the absence of topographic or man-made barriers (e.g. development), resulting in the conversion of existing upland habitats to wetlands. There are many locations in the coastal plain of North Carolina where these ecological transformations are already occurring, as evidenced by the presence of ghost forests (i.e. stands of dead trees as a result of saltwater intrusion). For example, Alligator River National Wildlife Refuge has already experienced transgression of marshes into upslope forested and pocosin wetlands (Ury et al. 2021, Smart et al. 2020).

Coastal wetlands have the capacity to build elevation through a combination of trapping sediments that are deposited by the tides, and production of below ground roots and rhizomes which contribute to soil volume (Cahoon et al. 2021). The rate at which a coastal wetland builds elevation is dependent upon the frequency, duration, and depth of tidal flooding it experiences, local suspended sediment concentrations, and plant biomass, among other factors (French and Spencer 1993, Kirwan et al. 2010, Davis et al. 2017). There are also forces that result in loss of elevation, including subsidence, sediment compaction, decomposition, and erosion (Morris et al. 2016). The relative contribution of these factors to coastal wetland elevation trajectory can vary considerably over space and time among coastal wetlands.

Given the complexity of coastal wetland response to SLR and subsidence, there has been significant interest in recent decades in measuring changes in wetland surface elevation. One tool that has been used extensively for this purpose since the 1990s, is the surface elevation table (SET; Cahoon et al. 2002). SETs provide powerful insight into the vulnerability of a given wetland to increasing water levels by providing precise measurements of sediment surface elevation change over time (Figure 1). SETs have been used all around the world (installed in at least 22 countries, and 22 states in the US) to measure coastal wetland resilience to SLR (Webb et al. 2013). In North Carolina, SETs have been installed across the coastal plain by a variety of researchers and land managers. In most cases, the existing SETs were installed to address site-specific research or management questions and without intentional coordination among the different groups of researchers.

In 2018, the North Carolina Surface Elevation Table Community of Practice (NC SET COP) was formed with the goal of identifying and mapping all of the previously installed SETs in the state, increasing collaboration among SET users, and working toward a synoptic analysis of the response of North Carolina coastal wetlands to SLR. The formation of this group was predicated on the realization that despite the independent nature of these various SETs, a coordinated analysis of SET-recorded elevation trends would provide invaluable insight into spatial variability in, and drivers of, elevation change in North Carolina's coastal wetlands. The synthesis described here represents the result of a systematic effort by members of the NC SET COP to analyze and interpret all existing SET-measured elevation trends statewide. Our goal is to provide a comprehensive understanding of North Carolina wetland trajectories that can help coastal managers prioritize mitigation, adaptation, and conservation actions. Additionally, we evaluate potential management actions that have been taken to restore coastal wetlands, provide input on the effectiveness of those actions, and insights on how they may best be used to navigate coastal wetland transformation moving forward.



What is a Surface Elevation Table?

SETs measure changes in the elevation of a wetland surface relative to a stable benchmark. To measure elevation change, a horizontal arm with nine pins is inserted into the top of the SET benchmark and is rotated between 4-8 positions. The height of nine pins above the arm is measured and compared to the first reading when the SET benchmark was installed. With repeated measurements over time, SETs can provide an unequivocal, high-precision record of elevation change that is directly comparable to local changes in sea level.

Figure 1. Profile of installed SET with horizontal arm and measurement pins. Adapted from Cahoon, 2015.

SET DATA SYNTHESIS

This product is the result of a collaborative, word-of-mouth effort to identify all SETs installed across the North Carolina coastal plain. While we have attempted to be exhaustive in our search for SETs, it is possible that there are additional devices that we have missed. The first product of this effort was a database and mapping tool (https://ncseagrant.ncsu.edu/ncSET) that provides consistent metadata records for each site including the location, year of installation, geomorphic setting, dominant vegetative community, reading frequency, history of experimental manipulations (eg. fertilization, burning, etc.) and direction of elevation trend of all 150 identified SETs. The mapping tool became active in 2020, and since that time we have worked as a group to synthesize and interpret the elevation data recorded at each device. To accomplish this, all partners were asked to contribute information on measured elevation trends and starting position within the tidal frame for each SET in their inventory. The specific parameters provided for each SET are listed in Table 1.

Table 1. Data contributed by each partner to facilitate analysis of trends among devices. *Calculated from local tide gauge data or estimated from NOAA VDatum tool (Parker 2002).

PARAMETER	NOTES
First Read Date	To calculate full length of record
Final Read Date	
Elevation trend and uncertainty	Calculated over full length of record
Marsh surface elevation at first read date	For determination of SET position within the local tidal frame
Site Mean High Water	
Site Mean Low Water	
Source of Water Level Datums*	

Elevation trends were calculated according to the method outlined by Lynch et al (2017). Briefly, this involves the linear regression of elevation change over time for each of the 36 pins (nine pins per SET 'arm' with four arm positions at 90 degree offsets), then averaging the nine pin slopes for each arm position. The average and standard deviation of the four arm slopes are then reported to represent elevation change for each device. We did not attempt to standardize data collection or QA/QC efforts among partners. Further, we did not include any SETs for which the data record spanned less than 5 years. Since our original effort to identify and locate all North Carolina SETs, an additional six have been installed, bringing the total to 156. Of the 156 SETs, 24 have associated data records that are less than 5 years in length and thus are omitted from this analysis. In all, 132 SETs are included in the full data analysis presented here.

The SETs included in this analysis were installed in varying configurations within their respective wetland complexes. In most cases where SETs were installed for the sole purpose of long-term elevation monitoring, they were installed in clusters of three devices at similar elevations. When SETs were installed to address a particular research question, the installation configuration was often tailored to the research question and as a result, the number of devices at each site ranged from one to six. In some cases, the data records associated with each device represent regular, relatively evenly spaced collection efforts (e.g. annual readings). In others, the time between readings has varied over time. Many of the older devices (data records longer than 10 years) have multi-year gaps between reads. While most are still actively read (final read dates 2022 or 2023), there are six that have not been read since 2016, and another 16 that have not been visited since 2018. For the purpose of this analysis, we treated each device as an independent observation regardless of spatial proximity. Overall, the 132 SETs represent 36 distinct wetland complexes (Figure 2).

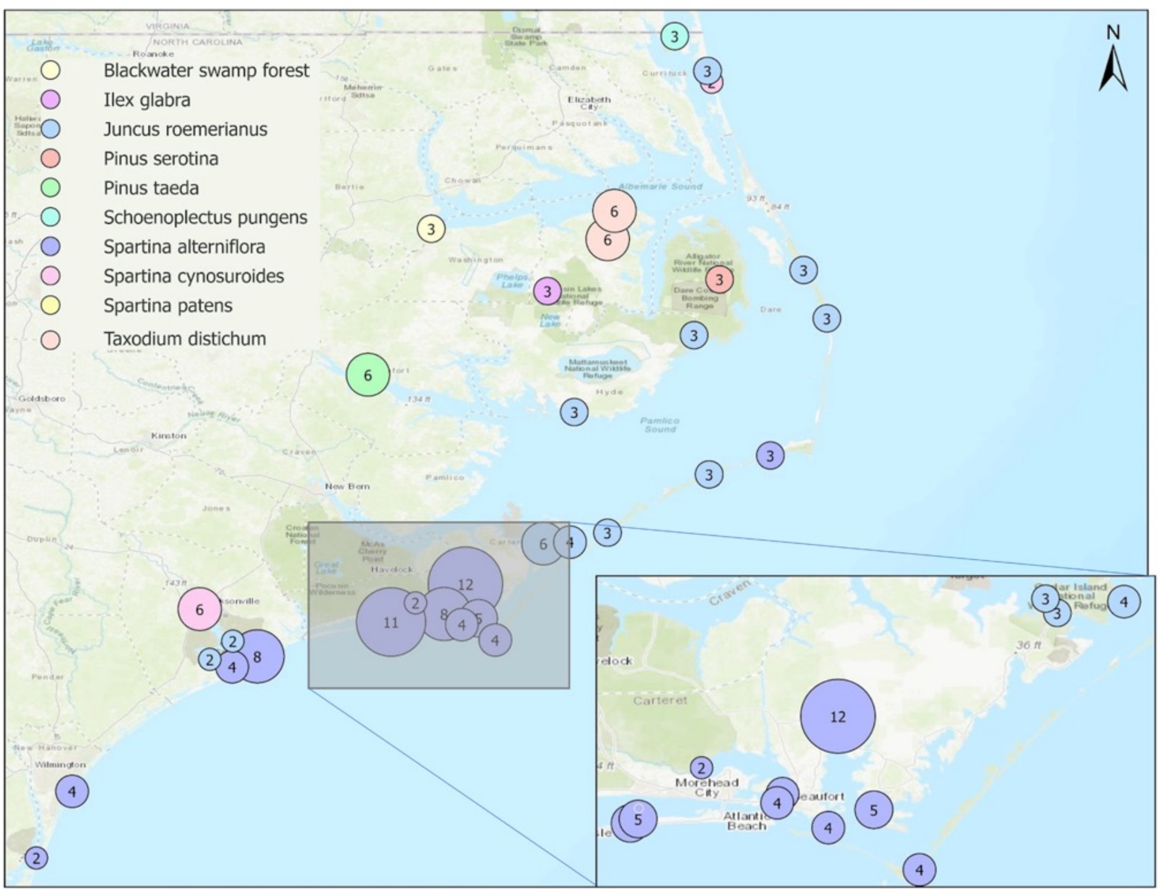


Figure 2. SETs in North Carolina. Circle size and values indicate the number of devices installed at each location. Circle color indicates the dominant plant community at each site. The inset shows areas with greater SET densities at higher resolution. Map Source: Esri, World Topographic Basemap, 1:2,375,000.

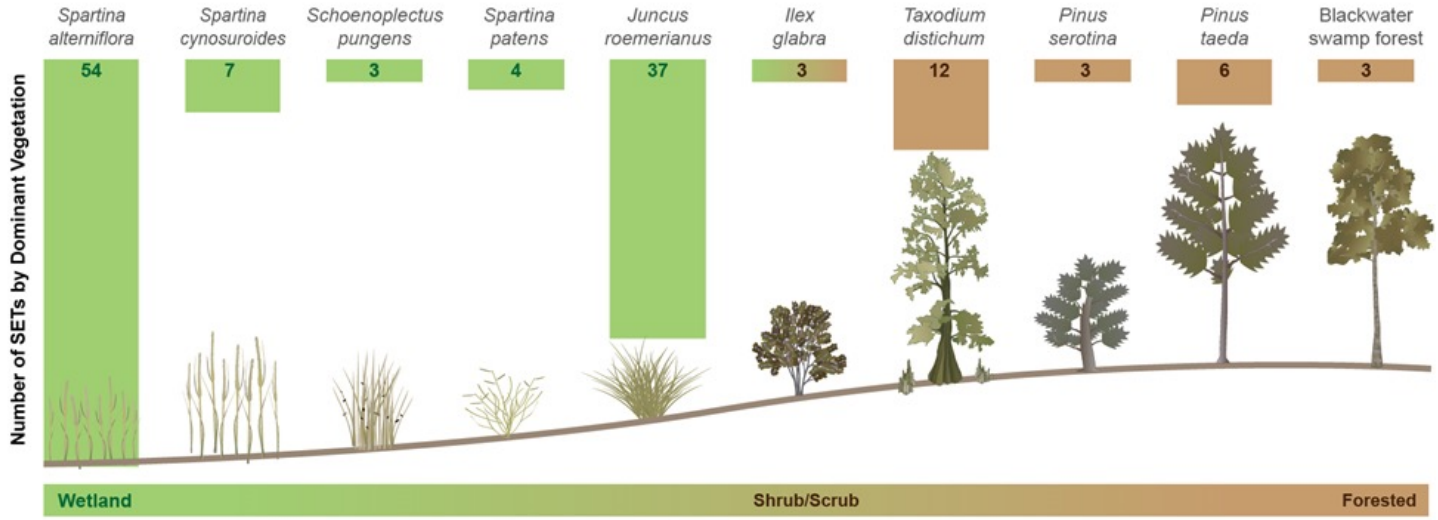


Figure 3. Distribution of installed SETs by dominant vegetation type. Symbols modified from the Integration and Application Network.

The vast majority of SETs were installed in *Spartina alterniflora* or *Juncus roemerianus* dominated marshes, which are the dominant wetland vegetative communities across coastal North Carolina (Figure 3). A number were also installed in coastal forests dominated by bald cypress (*Taxodium distichum*) and mixed blackwater swamp communities dominated by swamp laurel oak (*Quercus laurifolia*) and swamp maple (*Acer rubrum*). As of this writing, the length of data record associated with these SETs ranges between 5 and 30 years (Figure 4).

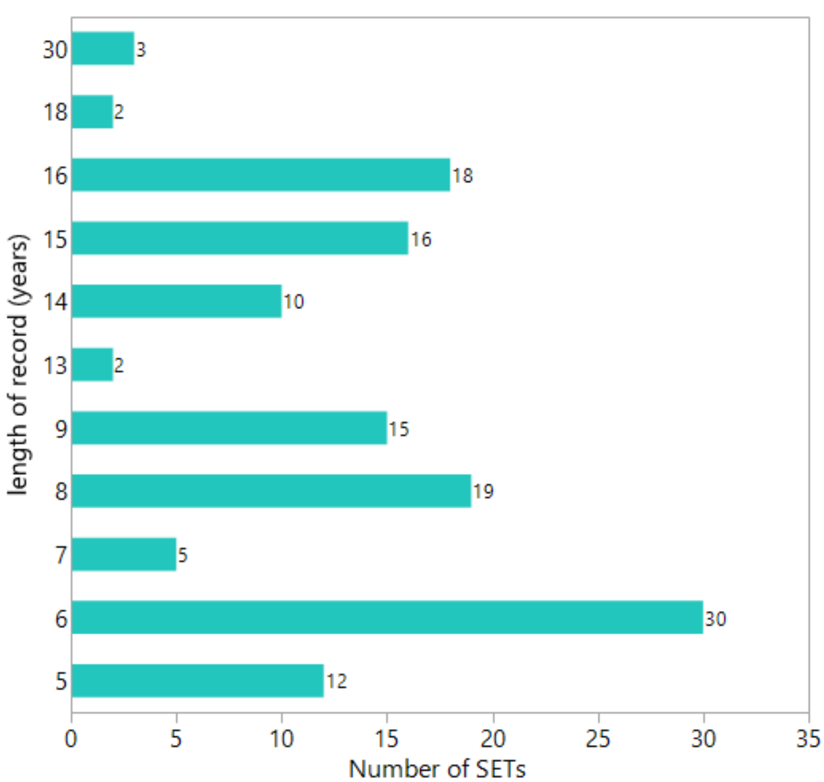


Figure 4. Length of data records associated with all SETs included in this analysis.

COMPARATIVE ELEVATION CHANGE AMONG SET SITES

The collected SET data were used to investigate whether distinctive trends in the rate of elevation change exist as a function of geographic location, wetland type, or dominant vegetation species. A subset of these SETs were intended to address questions about the efficacy of specific management strategies and in these cases, we compared elevation trends among treatments. The management strategies addressed include marsh-sill living shorelines, traditional wetland restoration, and nutrient fertilization.

At five sites, paired treatment and control SETs were used to investigate the influence of nutrient fertilization and associated plant responses on marsh elevation trajectory. Treatment SETs at Cedar Island and Pine Knoll Shores (Figure 5) were fertilized with commercially available granular fertilizer annually in 2006, 2007, and 2008. Additional

SETs at Freeman Creek, Mile Hammock Bay, and Onslow Bay were fertilized during two different iterations of experiments. The first experiment involved application of granular fertilizer three times during the growing season in 2008, 2009, and 2010 (Davis et al. 2017); the second involved quarterly fertilizer application from April 2015 through June 2016.

Another 16 SETs were installed as part of a targeted experiment to investigate differences in elevation gain between marshes behind shore parallel sills (i.e., living shorelines) and adjacent natural fringing shoreline marshes. At four independent sites (Harkers Island, Pivers Island, Pine Knoll Shores, and the NC Maritime Museum; Figure 4), a pair of SETs were installed in marsh sill living shorelines and two additional SETs were installed in nearby natural reference shorelines. In each pair, one SET was within 2 meters of the lower edge of *S. alterniflora* distribution, in the regularly flooded portion of the marsh, and the other SET was installed at the upper edge of *S. alterniflora* distribution, at the transition between low and high marsh.

In addition, there were clusters of SETs installed in three different wetland restoration sites including: 1) a brackish *Spartina cynosuroides* dominated shoreline wetland in Wilson Bay; 2) both *S. alterniflora* and *S. patens* dominated regions of a restored wetland along Deep Creek in North River Wetland Preserve; and, 3) a *Taxodium distichum* dominated wetland forest at Timberlake Observatory. In all three cases, additional SETs were installed at comparable elevations in nearby natural wetlands to serve as a reference.

The Timberlake Observatory for Wetland Restoration is a 440 hectare restored agricultural field (Ardón et al. 2010, 2017). Restoration included land movement (filling ditches and removing crowns), planting 750,000 trees, and removing a large pump that used to keep the 440 hectares dry for agriculture. SETs were installed in 2015, nine years after the start of restoration. Three SETs were installed in the northern part of the field, an area that has experienced saltwater intrusion, and three SETs in the southern part of the site, which has not experienced saltwater (Ardón et al. 2013). SETs were also installed in nearby Palmetto Peartree Preserve. This is an area on the shores of the Albemarle Sound that has been experiencing loss of forest and shoreline erosion (Taillie et al. 2019, White et al. 2022).

The North River Wetland preserve is a 14 hectare tidal marsh created by excavation of former agricultural land to intertidal elevation. The excavation was completed in 2006 and was followed by planting of 150,000 plugs of native emergent vegetation. In 2012, nine SETs were installed in the created marsh (triplicate SETs in each of three vegetation zones) and three additional SETs were installed in adjacent undisturbed marsh at corresponding elevations (one SET in each of the three vegetation zones) to serve as references. Wetland surface elevation was measured at all SETs from 2012 through 2017 and the data have been previously reported by Kamrath et al. (2019).

The Wilson Bay wetlands restoration involved conversion of a historic trash dump to wetland via excavation and removal of large debris in some areas, and fill placement in others. The created wetland is nine acres in area. After site preparation and grading

the area was planted with a mix of *S. patens*, *S. cynosuroides*, wax myrtles (*Myrica cerifera*), marsh elders (*Iva spp.*), red cedars (*Juniperus virginiana*), live oaks (*Quercus virginiana*), and bald cypress trees (*T. distichum*). Final planting was completed in 2002 and the SETs were installed in the summer of 2016.

WETLAND ELEVATION TRENDS IN RELATION TO SEA LEVEL RISE

In the ideal scenario, a water level sensor would be installed adjacent to every cluster of SETs to provide for a direct comparison of simultaneous trends in

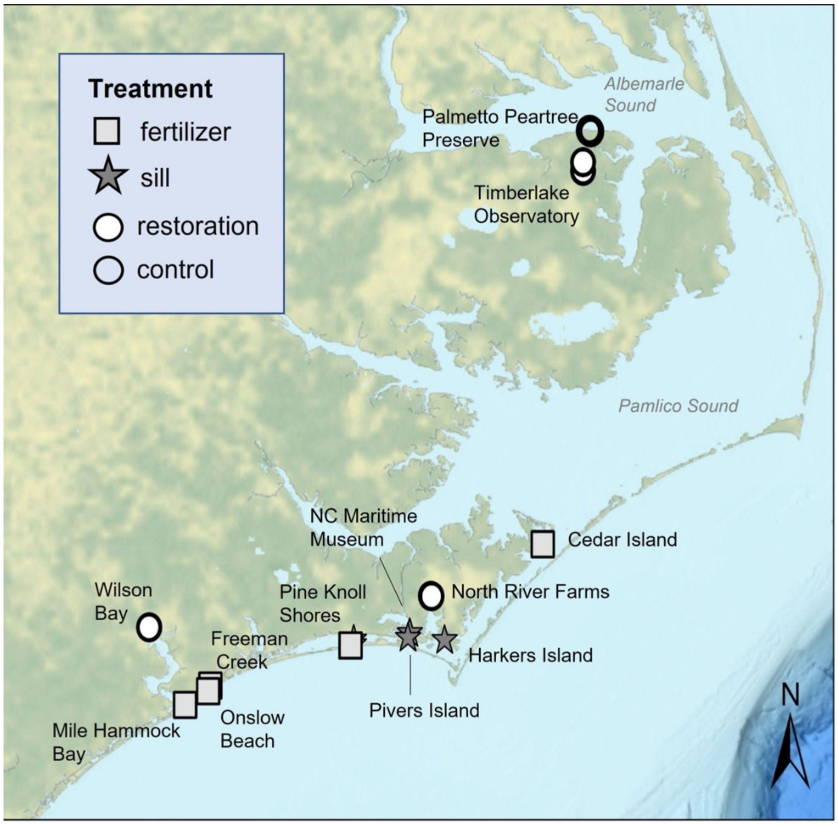


Figure 5. Locations of treatment-associated SETs. Palmetto Peartree Preserve serves as the control site for Timberlake Observatory. At all other sites, controls (not shown here) are present in close proximity to the treatment SETs. Fertilizer and sill treatments at Pine Knoll Shores are spatially distinct. Map Source: General Bathymetric Chart of the Oceans (GEBCO); NOAA National Centers for Environmental Information (NCEI)

wetland surface and water level elevations (Cahoon 2015). In practice, this rarely happens because it is far more labor intensive to maintain water level sensors than SETs and, as a result, we must rely on the closest available water level data. For this analysis, the relative position within the local tidal frame was calculated as:

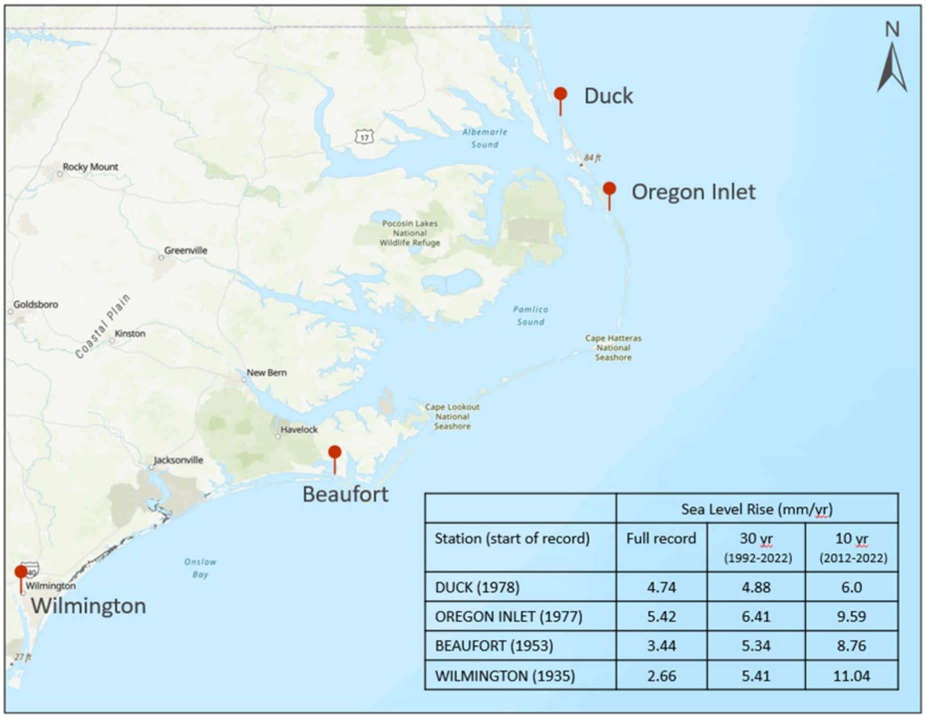
Relative position = (initial marsh surface elevation-MHW)/(MHW-MLW)

In the equation above, MHW is mean high water, and MLW is mean low water. Surface elevation and tidal datums were reported as meters referenced to NAVD88. By this calculation, a value of 0 indicates an elevation equivalent to that of MHW, and a value of -1 indicates an elevation equivalent to that of MLW. It is not possible to calculate this value for SETs that are in non-tidal regions (n = 21). For the rest, this value provides a relative estimate of resilience to further relative SLR as marshes that are lower in the tidal frame are at greater risk of converting to open water sooner as sea level rises.

Trends in relative SLR are spatially variable at the geographic scale of the coast of North Carolina due to differences in the rate of subsidence (Ohenhen et al. 2023). They also vary over multiple temporal scales due to differences in water temperature, dominant wind conditions, ocean circulation, global precipitation/evaporation balances, and planetary alignment. This variation occurs against a background of net increases in ocean volume due to warming. As a result, shorter-term calculated SLR trends tend to have wide confidence intervals (lower associated precision). For this reason, direct comparison among locations requires analysis of data that span consistent time ranges. Additionally, longer data records result in narrower confidence intervals and therefore increased ability to detect true differences among stations (Zervas et al. 2009). However, due to recent accelerations in SLR, particularly in the southeastern US, these longer-term trends rarely represent the conditions experienced on the ground during the period of SET data collection (length of SET records included in this analysis = 5 to 30 years).

The published value from each station is the rate of change over the full data record. These values, which are frequently referenced in discussions of local SLR, are strongly impacted by the length of time for which each station has been active. We calculated the rates of SLR for the most recent 10 and 30 years at the four National Water Level Observation Network (NWLON) stations in North Carolina for which data is available for the time period of interest: Duck (ID 8651370), Oregon Inlet (ID 8652587), Beaufort (ID 8656483), and Wilmington (ID 8658120). All water level data used here are available at: (NOAA Tides & Currents Relative Sea Level Trends). These are the same stations used to develop the state of North Carolina's 2015 Sea Level Rise Report (North Carolina Coastal Resource Commission, 2015). Rates were calculated as the slope of a linear regression of monthly mean sea level over time.

Among these stations, the long-term rate of SLR is inversely proportional to the length of the data record, while the shorter 30- and 10-year rates are substantially greater (Figure 6). This relationship exists because rates of global SLR were substantially lower before ~1990 than after (Gehrels 2021). A coarse analysis of recent temporal trends in sea level in the study area indicates that the 10-year trend is between 1.2 and 2 times greater than the 30-year trend (Figure 6).



	Sea Level Rise (mm/yr)		
Station (start of record)	Full record	30 yr (1992-2022)	10 yr (2012-2022)
DUCK (1978)	4.74	4.88	6.0
OREGON INLET (1977)	5.42	6.41	9.59
BEAUFORT (1953)	3.44	5.34	8.76
WILMINGTON (1935)	2.66	5.41	11.04

Figure 6. Rates of relative sea level rise over the most recent 10 years, 30 years, and over the full data record associated with each station. Only stations with at least 30 years of data were included in this analysis. All water level data used here are available at tidesandcurrents.noaa.gov. Map Source: Esri, World Topographic Basemap, 1:3,172,783.

SET-MEASURED ELEVATION CHANGE

SURFACE ELEVATION TRENDS IN EMERGENT WETLANDS

Emergent wetlands (i.e. marshes) are characterized by herbaceous non-woody vegetation. In the context of this effort, emergent wetlands are those sites dominated by *J. roemerianus*, *Schoneplectus pungens*, and *Spartina spp*. In total, 105 of the 132 SETs analyzed here are installed in emergent wetlands that span a range of salinities and tidal ranges. SET-measured elevation change rates at these marshes varied from a low of -20.47 mm yr^{-1} at a site where shoreline erosion resulted in the conversion of the area surrounding the SET from marsh to open water, to a high of + 10.22 mm yr^{-1} in a low-lying marsh that is near an inlet. Thirty-five of the 105 SETs in marshes (33%) recorded a net loss of elevation over their respective full length of record, while the remaining 70 sites experienced net surface elevation gains. There was no relationship between length of SET data record or dominant vegetative species, and measured surface elevation change rate.

Among all SETS that are installed in marshes, 10 (9.5%) measured elevation changes greater than the average 30-year rate of SLR and none measured changes greater than the 10-year rate. Of those 10, four are near an inlet that is likely importing sediment, and three are on the estuarine shoreline of Currituck Banks in a non-tidal setting. The remaining three are installed in shoreline fringing marshes at Pine Knoll Shores (Figure 5), where two are in a marsh-sill living shoreline and the third is in an area with unusually high standing plant biomass. Aside from these unique examples, marshes in North Carolina are failing to build elevation at a rate commensurate with recent (and in most cases, even long term) SLR.

Twenty-one of the 105 marsh SETs are installed in marshes that experience irregular flooding as a result of wind-driven tides rather than regular daily flooding from astronomical tides. These sites can experience inundation for days to weeks at a time depending on dominant wind conditions, and drying for equally long intervals. Among these 21 SETS, only 3 (those described above at Currituck Banks) have built elevation at a great enough rate to keep pace with the 30-year rate of SLR.

The remaining 84 marsh SETs are installed in marshes that experience regular daily flooding. Among these sites, comparison of marsh surface elevation trends by starting position within the tidal frame indicates that the greatest rates of elevation gain occurred in marshes that are at elevations slightly above local mean sea level (MSL, represented by relative starting elevation of -0.5; Figure 7). The four marsh SETs that lost elevation at rates of greater than 10 mm yr^{-1} were in shoreline fringing marshes. In all four cases, the corresponding data

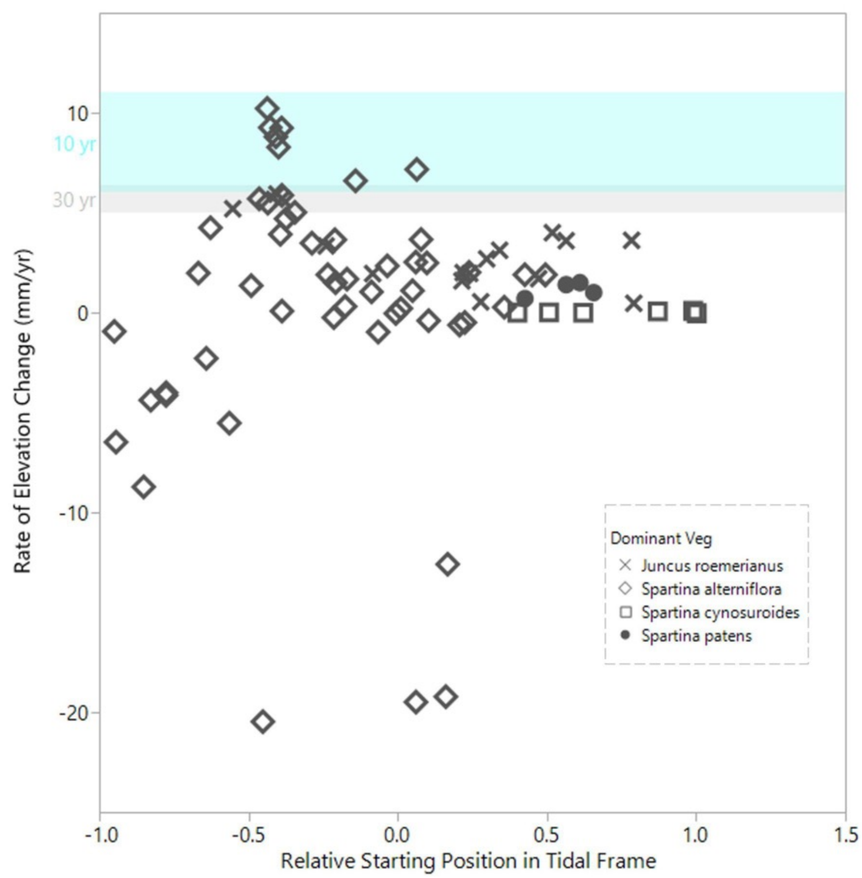


Figure 7. Surface elevation change rates measured by SETs installed in marshes that are impacted by astronomical tides. Position in tidal frame is relative to MHW. Grey shading represents the range of 30-year sea level rise rates calculated for NOAA's NWLON stations at Duck, Oregon Inlet, Beaufort and Wilmington, blue shading represents the range of 10-year rates for those same stations.

record was greater than 13 years in duration and over that time, the marsh edge receded to such an extent that the SETs were left in open water (Figure 8). These four SETs have become too unstable for further use, and we are aware of at least six more that are likely to suffer the same fate in the near future.

SURFACE ELEVATION TRENDS IN SCRUB/SHRUB AND FORESTED WETLANDS

A total of 27 SETs have been installed in forested wetlands and upland transitional habitats. The habitats included in this category are characterized by woody vegetation (Figure 3). While elevation growth in coastal marshes is supported by the deposition of sediment during flood tides, the same is not true of forested wetlands (aside from swamp forest). These sites, due to their higher position in the tidal frame, only experience flooding above ground level in extreme conditions as opposed to cyclical flooding from astronomical tides. As a result, their primary mechanism of elevation gain is through the production of root material (Stagg et al. 2016). Of the forested wetland sites included here, only the swamp forest experiences regular inundation. The swamp forest SETs exhibited the highest rates of elevation gain (3.4 mm yr^{-1}; Figure 9).

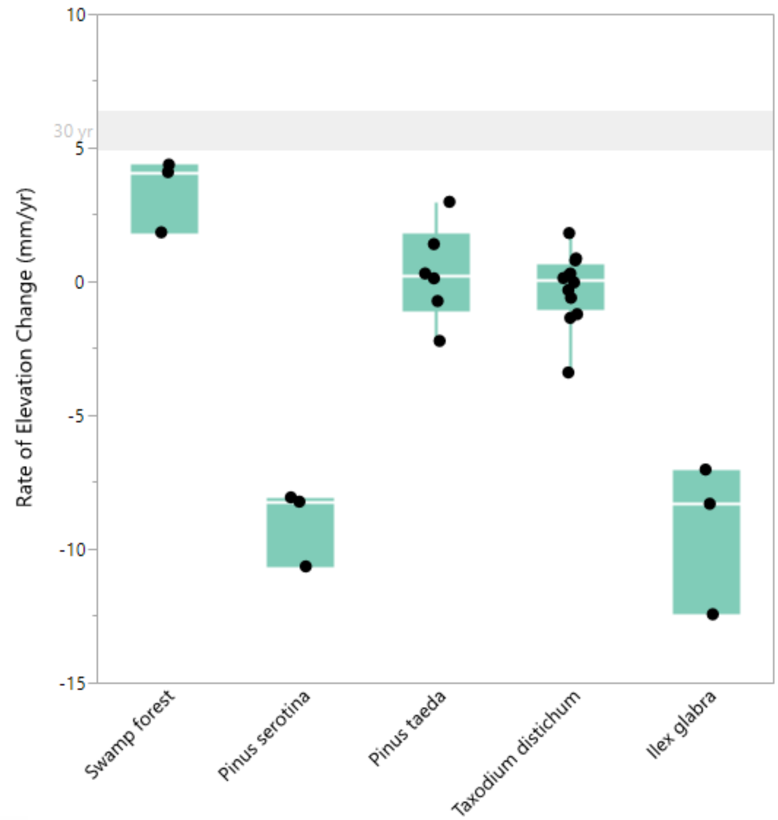


Figure 9. Surface elevation change in forested wetlands and upland transitional habitats. The swamp forest site is dominated by *Quercus laurifolia* (Laurel oak), *Acer rubrum* (Swamp maple) and *Fraxinus pennsylvanica* (Green Ash). The sites dominated by *Ilex glabra* (Inkberry) and *Pinus serotina* (Pond Pine) are a unique forested wetland habitat type known as Pocosin, that form on top of deep domes of organic peat. *Pinus taeda* (Loblolly pine) and *Taxodium distichum* (Bald cypress) dominated sites are upland habitat. Grey shading represents the range of 30-year SLR rates calculated for NWLON stations at Duck, Oregon Inlet, Beaufort, and Wilmington.

Figure 8. Shoreline change around a SET installed in a natural fringing marsh shoreline in Pine Knoll Shores, NC. Red circled denotes location of SET in 2006 (top panel) and 2019 (bottom panel).

Presumably that gain was driven by root zone expansion rather than particle deposition because no measurable sediment accretion was observed (Moorman et al, 2023). While none of the forested or upland habitats gained enough elevation to keep pace with relative SLR, the two sites classified as pocosin which are located on peat domes (dominated by *Ilex* *glabra* [inkberry] and *Pinus serotina* [pocosin pine]) lost elevation at appreciable rates (-9 mm yr^{-1}; Figure 9). The subsidence rates were less than half of those previously published for pocosin habitats (-20 mm yr^{-1}, Richardson 1983), likely because the selected sites had minimal alterations to hydrology.

EFFECTIVENESS OF SELECT RESTORATION STRATEGIES AT MAINTAINING WETLAND ELEVATION

Marsh Sills

In all cases, SETs in marsh sill living shorelines measured net positive elevation gain. In contrast, only two of the eight SETs installed in paired reference marshes measured net increases in elevation over time. At all sites other than Harkers Island, the difference between natural and sill SETs was most pronounced at lower relative elevation.

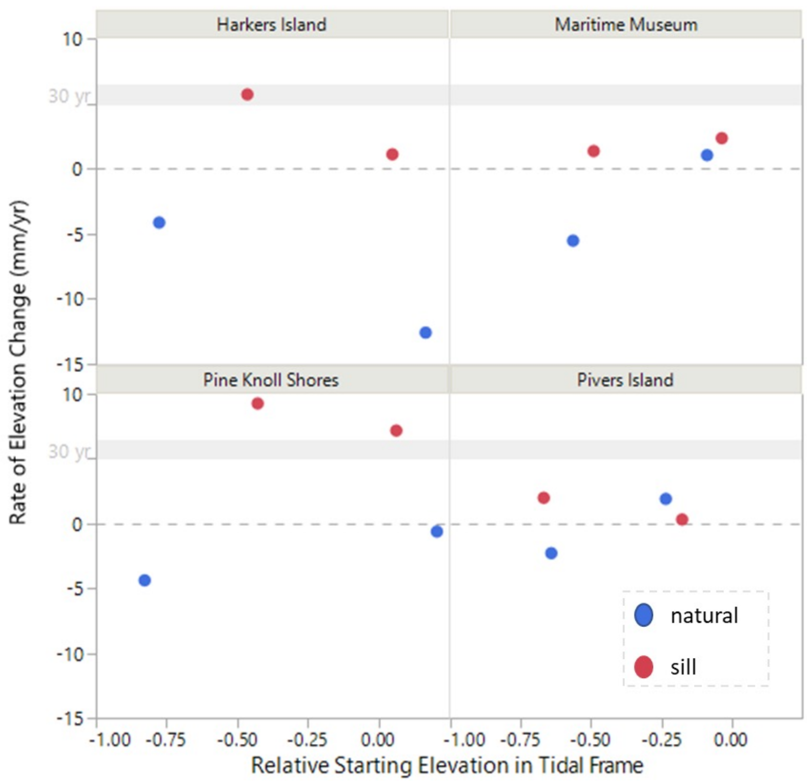


Figure 10. Elevation change rate as a function of relative position in the tidal frame at marsh sill living shorelines and paired reference marshes. Data records associated with these 16 SETs range in duration from 13 to 16 years. Grey shading represents the range of 30-year sea level rise rates calculated for NOAA's NWLON stations at Duck, Oregon Inlet, Beaufort, and Wilmington.

Only three of the of the marsh sill living shoreline SET sites gained elevation fast enough to keep pace with SLR over the past 30 years and all three were in marsh sill living shorelines (Figure 10).

Fertilization

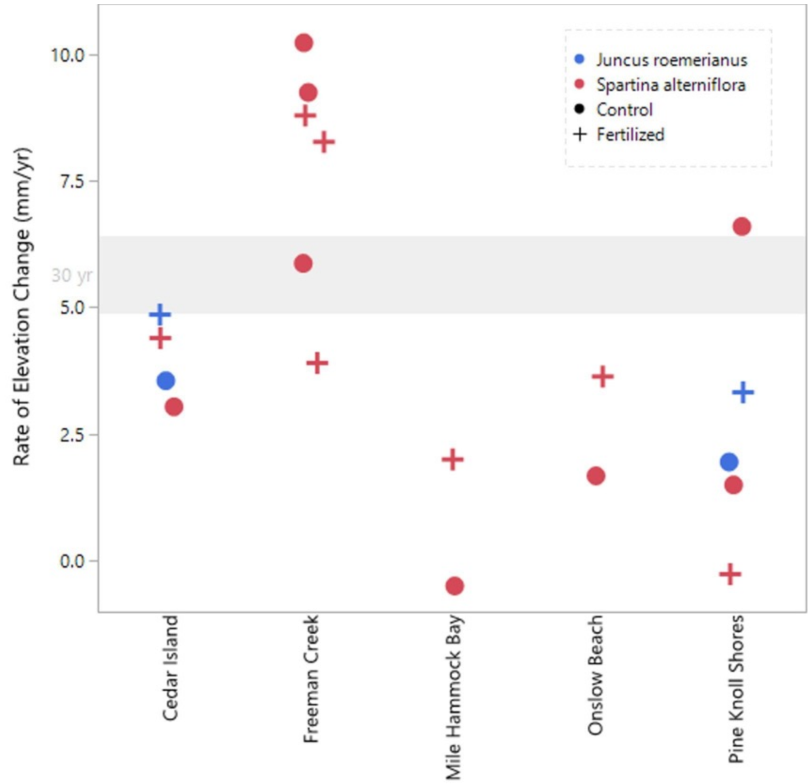
The long-term impacts of nutrient fertilization on surface elevation were variable by site and dominant vegetation type (Figure 11). At the Freeman Creek site, fertilized plots gained less elevation over the full extent of the SET record than control plots. At Cedar Island, fertilization resulted in greater elevation gain in both *S. alterniflora* and *J. roemerianus* dominated plots. At Pine Knoll shores, fertilizer addition resulted in greater long-term elevation gain in *J. roemerianus* but not in *S. alterniflora*, while at both Mile Hammock Bay and Onslow Beach, fertilizer addition resulted in greater elevation gain in *S. alterniflora* plots.

Wetland Restoration

The elevation trajectories in restored wetlands relative to reference sites, varied by location. At Wilson Bay, there was minimal elevation change in restored (avg = 0.02 +/- 0.02 mm yr^{-1}) or natural marsh shorelines (avg 0.08 +/- 0.04 mm yr^{-1}). At North River, the restored sites appear to be gaining elevation at equivalent to or greater rates than the nearby reference marsh (Figure 12; Kamrath et al. 2019). Two of the restored marsh SETs documented elevation change rates greater than the long-term rate of SLR at the nearby Beaufort tide station (3.44 mm yr^{-1}: Figure 6). Both of those SETs were installed in *J. roemerianus*- dominated portions of the restored marsh.

For the current analysis, Palmetto Peartree Reserve serves as the natural reference for the Timberlake Observatory restoration site. Measured rates of elevation change at Timberlake Observatory ranged from -0.32 to + 0.86 mm yr^{-1} while those at Palmetto Peartree ranged between -3.4 and + 1.8 mm yr^{-1}; Figure 9). None of the treatment or control wetlands built elevation at a rate commensurate with the 30-year rate of SLR.

Figure 11. Impact of nutrient fertilization on marsh elevation trajectory. The length of SET data record was 8 years at Freeman Creek, 14 years at Mile Hammock Bay and Onslow Beach, and 16 years at Cedar Island and Pine Knoll Shores. Grey shading represents the range of 30-year sea level rise rates calculated for NOAA's NWLON stations at Duck, Oregon Inlet, Beaufort, and Wilmington.



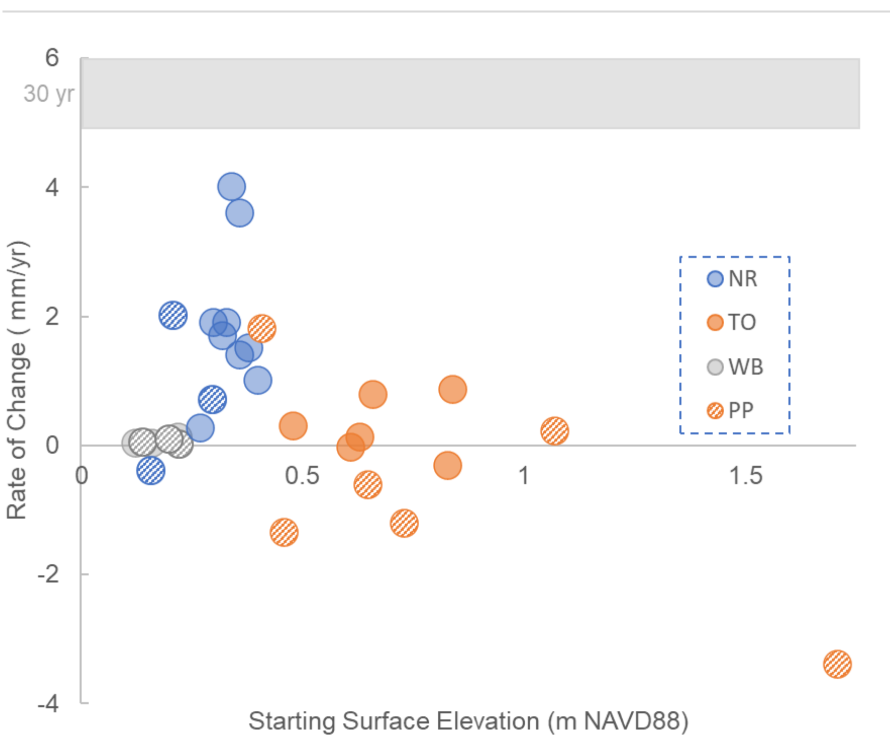


Figure 12. Elevation change in restored wetlands. NR = North River Wetland Preserve, TO = Timberlake Observatory, PP = Palmetto Peartree Preserve, WB = Wilson Bay. Solid circles represent SET plots in restored sites, hatched circles represent SET plots in control wetlands. Grey shading represents the range of 30-year sea level rise rates calculated for NOAA's NWLON stations at Duck, Oregon Inlet, Beaufort, and Wilmington.

PLANNING FOR THE FUTURE

SET-measured elevation trends signal a concerning future for North Carolina's coastal wetland habitats. Of 132 total SETs evaluated here, 25% (33 SETs) documented net losses in elevation. Among those that documented elevation gains (99 total), 79 did not gain elevation at a fast enough rate to keep pace with the lower end estimates of SLR over the past 30 years (4.4 mm yr^{-1}) and only 10 gained elevation at a fast enough rate to keep up with SLR over the past 10 years. Continued deficits in elevation gain with respect to SLR will inevitably result in the conversion of many areas that are currently coastal marsh to open water habitat as was documented in two locations by this analysis (Figure 8). Where elevation gradients and current land use allow, coastal wetlands may migrate upslope as sea level rises. This inland transgression is already visibly evident in many areas of the central inland coast as indicated by the presence of ghost forests with marsh understory (Ury et al. 2022, Smart et al. 2021, Phillips 2024, Kirwan and Gedan 2019).

Recent model-based projections of the future distribution of North Carolina wetlands under SLR suggest that the vast majority of the existing 85,500 hectares of coastal marsh will be lost by the year 2100. Approximately 50% of this loss is predicted to be offset by marsh transgression into areas that are currently upland/transitional habitats (Warnell et al. 2022). This could result in significant conversion and loss of forested wetlands to ghost forest and subsequently, to salt marsh (Osland et al. 2022). Most of the area available for transition (i.e. currently undeveloped and with minimal topographical barriers to marsh migration) is in the inland shoreline of the Albemarle-Pamlico Sound. Marshes in other parts of the state will face the additional challenge of having limited opportunity to migrate upslope. Agreement between model-predicted and SET-measured responses of North Carolina's coastal wetlands to SLR highlights the need to plan for significant future losses of total wetland extent, and to implement management and restoration actions to minimize those losses to the extent possible.

Among the marsh SETs, we observed greater rates of elevation gain in marshes that are currently near or just above the elevation of local mean sea level (MSL). This distribution is predicted by the geomorphic feedback mechanisms that control marsh response to SLR (Morris et al. 2002). The biomass of marsh vegetation generally exhibits a parabolic relationship with elevation where plant biomass reaches a maximum at elevations near MSL but decreases incrementally with distance in either direction from MSL (Kirwan and Guntenspergen 2015). This trend occurs because, at lower elevations, plants become increasingly stressed by long inundation times; while at higher elevations, they become stressed by high porewater salinities and lack of porewater exchange. As a result of the greater plant biomass that often occurs near MSL, marshes at this elevation are more efficient at building additional elevation through both the trapping of sediments from the water column, and root zone expansion. One important consequence of this pattern of growth is that as sea level (and therefore the elevation of MSL) increases, marshes that are currently higher than MSL elevation may initially experience enhanced plant growth and as a result, increased rates of elevation gain. Modeled predictions suggest that despite potential short-term gains these sites will ultimately not be able to keep up with SLR (Fitzgerald and Hughes 2019).

Restoration and Conservation Opportunities

There are several management options available for increasing the resilience of coastal wetlands to continued SLR. Marsh-sill living shorelines can provide protection against erosion and, as demonstrated here, sills can help to promote elevation gain. Sediments dredged from navigation channels can be used to increase surface elevation of existing wetlands, and to restore eroded wetland habitats to their former extents (Thorne et al. 2019, Davis et al. 2022). Runneling (creating shallow drainage channels) can restore natural hydrology to high elevation wetlands that suffer from ponding (Watson et al. 2022). Similarly, filling mosquito ditches can restore natural hydrology to previously altered wetlands (Burdick et al. 2020). In some cases, the best management option may involve ensuring that there is space available for marshes to migrate inland. While there are many tools available to promote marsh survival into the coming decades, the magnitude of the challenge is massive. Clearly, it will not be possible to preserve or restore the greater than 40,000 hectares that are predicted to be lost. Empirical evidence like that provided by SETs, in combination with modeled projections of future habitat change, can be a powerful resource for guiding decisions about how and where to focus limited resources for maximum benefit.

Shoreline-Fringing Marshes

Among North Carolina coastal wetlands, the narrow fringing marsh shorelines that are common from Bogue Sound to the southernmost parts of the state will likely face some of the most immediate challenges with respect to SLR. In many cases, steep topographical gradients at the upland edges of these marshes limit their overall width and their ability to migrate upslope. As a result, building elevation at a rate commensurate with SLR is their only option to avoid drowning. The challenges that these sites face is compounded by wave-induced erosion of their shoreward edges. While fringing marshes are generally small in footprint, they have an outsized influence on local ecology and fishery production, as the highest densities of nekton within a marsh tend to occur within a few meters of the shoreline edge (Peterson and Turner 1994; Minnelo and Zimmerman 1994). Living shoreline techniques employed either alone or in combination with sediment placement to rebuild eroded fringing marsh can help to promote resilience of fringing marsh shorelines to future SLR. As the data presented show, this approach does not provide a permanent solution to the challenges of fringing marshes. Despite gaining elevation at higher rates than natural fringing shorelines, the marsh-sill living shorelines analyzed here have not kept pace with recent rates of SLR (Figure 7). Familkhalili et al (2022) modeled the fate of a Carteret County fringing marsh under multiple future SLR scenarios with and without a proposed marsh sill in place. This analysis projected significantly more marsh habitat in the sill-reinforced shoreline through mid-century, but diminishing returns after that point as SLR ultimately outpaced even the sill-marsh's ability to build elevation.

Back-Barrier Marshes

An expansive system of back-barrier marsh occurs from Bogue Inlet south to the mouth of the Cape Fear River. Along the full extent, this marsh system is bounded by a beach and dune complex at its seaward extent and by the Atlantic Intracoastal Waterway at its inland extent. A narrower fringe of backbarrier marsh extends from Cape Lookout to the north. These marshes tend to be relatively high in the tidal frame (calculated relative position near, or greater than 0) presumably as a result of landward transport of sand from the beach face via aeolian transport and storm-related washover events (Walters et al. 2014). The potential influence of this sand subsidy is illustrated in data from Cape Lookout where one of the SETs recorded an elevation change rate of -16 mm yr^{-1} as a small dunelet feature migrated out

of the SET plot over time. While these backbarrier marshes are not immune to the challenges presented by SLR, many of them are currently high enough in the tidal frame that adding additional elevation would result in conversion of the existing marsh to a more upland/transitional habitat. Many of these marshes, particularly those north of Cape Lookout appear to be more immediately threatened by shoreline erosion which functions to narrow the entire barrier island. In these situations, using dredged sediments to rebuild backbarrier marsh to its historical extent may be the most effective strategy to promote marsh (and barrier island) resilience.

Wetlands of the Inner Shoreline

Estuarine wetlands in Albemarle-Pamlico Region face the double threat of high rates of shoreline erosion and low elevation; much of the region is within a few feet of current sea level (Corbett et al. 2008). The Albemarle-Pamlico region was recently identified as among the areas in the United States that are most susceptible to "catastrophic, landscape scale wetland loss" under a worst case future SLR scenario where current salt marshes aren't able to build elevation fast enough to keep pace, and where freshwater marshes collapse due to saltwater intrusion (Osland et al. 2022). Conversely, wetlands in this region also have a higher potential to migrate inland due to the gently sloping topography and low density of development. Private property ownership can present a barrier to wetland migration due to reluctance of some landowners to allow their property to passively convert to wetland. Extensive community level engagement and acquisition of parcels that can serve as migration corridors will likely be required to maximize the survival of wetlands in this region (Bergeson 2023).

Pocosins and forested wetlands face their own unique challenges. Much of the pocosin habitat on the Albemarle-Pamlico Peninsula, was previously ditched and drained for conversion to agriculture. This has resulted in lowering of the groundwater table, soil decomposition due to oxidation and saltwater intrusion, increased subsidence and inundation, and increased frequency of large, catastrophic peat fires (Faustini et al. 2020). Much of the inland gains that marshes can make through transgression will come at the expense of pocosin and forested wetlands (Osland et al. 2022). Horizontal transgression has already been observed in the low elevation forests at Alligator River National Wildlife Refuge in North Carolina where more than 19,000 hectares of forested wetlands have transitioned to marsh or shrubland habitat in the past 35 years, likely due to saltwater intrusion from storms and SLR (Ury et al. 2021). Transition of forested wetlands and pocosins to scrub-shrub and marsh habitat has been documented across the entire Atlantic coastal plain (White et al. 2022). This has implications for carbon storage, carbon cycling, and ecosystem function (Aguilos et al. 2021). Strategic acquisition and conservation of lands upstream and upslope are a critical component to conserving pocosins and forested wetlands in the future and has been recommended as a key conservation strategy (ACJV 2019). One example of this is an ongoing effort to expand the boundary for Roanoke River National Wildlife Refuge which could include the conservation of up to an additional 250,000 acres upstream and upslope in the Roanoke River watershed. SET-measured rates of shallow subsidence in pocosin wetlands suggest that rewetting of peat soils in these systems should be prioritized (Faustini et al. 2020, Moorman et al. 2023). Rewetting of these pocosin systems also decreases greenhouse gas emissions from formerly drained soils (Armstrong et al. 2022).

CONCLUSIONS

This synthesis of SET data for the state of North Carolina confirms the recommendation that coastal wetland conservation and preservation strategies should focus on building vertical elevation capital, protecting horizontal transgression spaces upslope and upriver, or creating new habitats inland (ACJV 2019). Conservation of transgression spaces including forested wetlands and pocosins is important, as they represent both an important habitat today, and the future transgression space for upslope migration of coastal marshes. Strategies aimed at effectively directing transgressions that are already occurring will need to be considered as landscape conservation designs are developed and implemented (Faustini et al. 2020; Ury et al. 2021, Osland et al. 2022). Finally, improving our understanding of the role of tidal regime on biophysical processes of coastal marshes and how each unique marsh system responds to restoration strategies, such as thin-layer sediment deposition, will help us better restore and maintain habitats in the near-term (McKee and Grace 2012, Powell et al. 2019, Faustini et al. 2020, Moon et al. 2022). An overall strategy that considers multiple approaches aimed at resisting, accepting, and directing (Lynch et al. 2022) transgression across the entire landscape will minimize the loss of coastal wetland habitats across North Carolina and the ecosystem services they provide.

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