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# Salt Marsh Migration Potential at Cape Cod National Seashore (Massachusetts, USA) in Response to Sea-Level Rise

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## ABSTRACT

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Salt marshes can adjust to sea-level rise (SLR) through vertical elevation gain and horizontal expansion into terrestrial environments. The latter depends on the topography of adjacent uplands and the availability of suitable substrate for halophyte colonization. Within Cape Cod National Seashore (CCNS), calculations of marsh migration potential in response to 1-m of SLR were completed using ArcGIS (version 10.4) based on real-time kinematic GPS marsh elevations, local tide data, land-use, and upland topography derived from 2011 LIDAR scans of CCNS. These estimates were combined with marsh-loss predictions from a previous study within their present-day footprint under the same SLR scenario. The results suggest that individual marshes will respond quite disparately, as dictated by their position in the tidal frame, terrestrial slopes, land-use, and barrier-beach losses. Most sites are expected to gain or lose relatively small amounts of marsh area under few or no migration constraints. However, there could be a large increase (~144–240 ha) at one site and an almost a complete loss at another (~260–290 ha). Where migration was constrained to slopes ≤1%, opportunities for marsh expansion diminished the most—even more so when barrier-beach losses are simulated. Overall, losses at five marsh sites were offset by gains at Hatches Harbor and Pleasant Bay, Massachusetts, such that the total area of salt marsh actually increases with 1-m of SLR, except under the strictest slope constraints. Changes in the spatial distribution and total extent of salt marsh within the CCNS will influence both the quality and quantity of ecosystem services they provide. For coastal land managers, understanding the potential for overland marsh migration is critical for the kind of land-use planning that accommodates these transitioning salt marshes.

**ADDITIONAL INDEX WORDS:** *Climate change, transgression, flooding, coastal.*

## INTRODUCTION

Anthropogenically driven sea-level rise (SLR) is one aspect of climate change that is affecting coastal ecosystems worldwide, including dunes, beaches, freshwater wetlands, mangroves, and salt marshes (Crosby *et al*., 2016; Feagin, Sherman, and Grant, 2005; Peter, 1997; Spencer *et al*., 2016; Valiela *et al*., 2018; Wanless *et al*., 1994; Watson *et al*., 2017; Woodroffe, 1990). For salt marshes, which occupy the niche between land and sea, adverse effects of SLR on growth and stability have been well documented (Orson, Panageotou, and Leatherman, 1985; Schuerch *et al*., 2018). Given their abundant and widely ranging ecosystem services, the diminishment of these systems is an important global issue (Craft *et al*., 2009; Shepard, Crain, and Beck, 2001).

Salt marshes can adjust to SLR through vertical elevation gain, which occurs mainly through peat accumulation and sediment deposition (Baustian, Mendelssohn, and Hester, 2012; Kennish, 2001; Kirwan and Murray, 2008; Syvitski *et al*., 2005; van Wijnen and Bakker, 2001). However, the importance of horizontal *vs*. vertical expansion increases once SLR exceeds the rate of vertical elevation gain (Brinson, Christian, and Blum, 1995; Brinson and Christian, 1999; Civco, Kennard, and Lefor, 1986; Donnelly and Bertness 2001; Orson and Howes, 1992; Raabe and Stumpf, 2016; Smith 2009; Smith, Medeiros, and Tyrrell, 2012; Smith, 2015a; Warren and Neiring, 1993). In coastal states of the northeastern United States, ~~vertical elevation gain~~ is primarily the result of belowground biomass accumulation given that sediment concentrations in coastal waters of this region are generally low (Bricker-Urso *et al*., 1989; Cavatorta *et al*., 2003; Turner, Swenson, and Milan, 2000; Weston *et al*., 2014).

Salt marsh migration into terrestrial zones partly depends on land-use and topography of adjacent upland habitat (Enwright, Griffith, and Osland, 2016; Feagin *et al*., 2010; Moorhead and Brison, 1995). Infrastructure, such as roads, parking lots, and manfactured structures, *etc*., will restrict, or in some cases prevent, transgression. Where there are lightly developed, seminatural, or natural areas (*e.g*., pastures, lawns, playing fields, and low-density residential), marshes may expand where slopes are gentle enough (Enwright, Griffith, and Osland, 2016; Kirwan *et al*., 2016). Steeply-sloped terrestrial borders limit salt marsh expansion through simple physics since a given rise in water level translates to a much shorter horizontal distance that it can penetrate. However, it appears that the degree of incline itself, even if within a suitable tidal range, may also inhibit the process. This is because the ground surface becomes quickly isolated from the effects of inundation as its elevation increases. Where there are more steeply-sloped dunes, water content tends to be much lower because storm pulses of salt water or rainwater tend to drain away quickly (Anisfeld, Cooper, and Kemp, 2017; James and Zedler, 2000)~~,~~ ~~although Fagherazzi *et al*. (2019) suggest that storm-related~~

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~~pulses of seawater may not penetrate as far across areas with gentle slopes because of friction from existing vegetation and travel distance~~. Lack of soil moisture can further limit halophyte colonization (He, Cui, and An, 2012), and this is particularly germane to dune and barrier–beach habitats, in which the sandy soils are almost completely lacking in organic material that would otherwise retain both moisture and nutrients. Increasing angle of incline also reduces shoreline stability and increases the susceptibility of colonizing plants to avalanching from wind and wave erosion (Pye and Tsoar, 2008; Qi *et al*., 2010). Conversely, gentle slopes generally allow for greater horizontal infiltration of seawater across larger horizontal distances, setting up a more gradual attenuation of soil moisture and salinity conditions between upper marsh and terrestrial substrate.

Within Cape Cod National Seashore (CCNS) (Massachusetts, USA), there are roughly 850 ha of salt marsh habitat. The highest rate of vertical elevation gain measured from surface elevation tables (SETs) situated in the low-marsh vegetation (*Spartina alterniflora*, smooth cordgrass) of three separate CCNS marsh sites is ~2.73 ± 0.16 mm/y (2000–2019; J. Lynch, unpublished data). This value is lower than local rates of SLR, which range from 2.83 ± 0.15 mm/y in Boston (1921–2018) to 2.88 ± 0.17 mm/y in Falmouth, Massachusetts (1932–2018) to 3.68 ± 0.17 mm/y in Nantucket, Massachusetts (1965–2018) (data from National Oceanic and Atmospheric Administration tide stations; NOAA, 2019). Accordingly, CCNS's salt marshes are expected to undergo substantial losses within their present-day footprints, as has previously been described by Smith *et al*. (2016) under conditions of 1-m of SLR by the year 2100. This scenario has a very high likelihood of occurrence (Church *et al*., 2013; Vermeer and Rahmstorf, 2009; Wright, Syvitski, and Nichols, 2019) and is quite conservative compared with a number of other sea-level models, some of which predict up to a 2.5 m rise by the century's end (Sweet *et al*., 2017).

To preserve as much of the resource as possible, it is critical that park management understand where there may be opportunities for marsh expansion into terrestrial environments. In this study, the potential for overland migration in CCNS salt marshes was assessed using GIS for a 1-m rise in sea level. High-resolution marsh and upland topography, land-use, and marsh loss estimates from Smith *et al*. (2016) provided the basis for ~~(1)~~ delineating areas in which expansion could occur, ~~(2)~~ how ~~various land-use and slope constraints may limit that process, and (3) how barrier beach erosion may be limiting to this process and to what extent marshes may expand or contract.~~

## METHODS

Seven areas that constitute most of the salt marsh habitat within the CCNS were analyzed in this study: Hatches Harbor (HH), West End (WE), the Gut (GU), Middle Meadow (MM), Jeremy (JM), Nauset (NS), and Pleasant Bay (PB) (Figure 1). A large proportion of CCNS's marsh habitat was previously estimated in Smith (2015a) and Smith *et al*. (2016) from August 2013 georeferenced eight-band satellite imagery (0.5 m spatial resolution) using ArcGIS. Marsh surface-elevation layers were based on real-time kinematic (RTK) surveys conducted in 2013 and described in Smith *et al*. (2016), whereas LIDAR data acquired in 2011 from the Natural Resource Conservation Service (NRCS) ~~was~~ used to create digital elevation models (DEMs) of the surrounding terrestrial landscape (3 m cell size, ±10 cm potential vertical error).

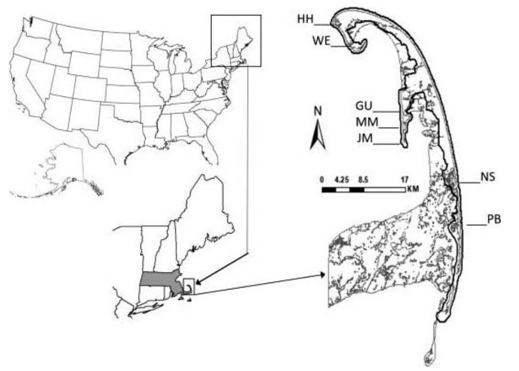

Figure 1. Map of the United States (top left), the Commonwealth of Massachusetts (bottom left; gray polygon), and outer Cape Cod with CCNS boundary (right; black polygon). Individual marsh indicated by their acronyms (HH = Hatches Harbor, WE = West End, GU = Gut, MM = Middle Meadow, JM = Jeremy, NS = Nauset, and PB = Pleasant Bay).

Tidal data (North American Vertical Datum of 1988) specific to each marsh embayment was available from the previous study by Smith *et al*. (2016). Those data originated from HOBO water-level loggers (accuracy of ±0.05 cm) placed in low-marsh vegetation at each site that collected data at 30-minute intervals from May 2013 to September 2013 (Smith *et al*., 2016). To simulate 1-m of SLR, maximum-tide height elevations (which approximate the upper boundaries of CCNS marshes in each system) were determined from the tidal data for each system spanning May–October 2013. Subsequently, those elevations were raised by 1-m, and the area between the two was calculated (henceforth, referred to as "potential migration areas" or "PMAs").

### Land-Use and Slope Constraints on Migration

Land-use categories derived from 2005 aerial photography were downloaded from the Cape Cod Commission (2017) GIS data portal. Land-use classifications were more coarsely divided into either "softscape" (relatively passive land-use or natural areas) or "hardscape" (more-developed areas with hardened infrastructure) as summarized in Table 1. Because of the lack of any standard methodology for classifying land-cover potential for salt marsh migration, land cover types within the CCNS were grouped into those two categories in an effort to err on the side of inclusivity for migration suitability. Subsequent GIS analysis of these groupings shows that, collectively, hardscape had greater than 50% impervious surface, whereas all softscape classes had <45% and, generally, below 30%.

Terrestrial slopes (based on LIDAR elevations) were determined using raster-processing functions in ArcGIS to generate triangular irregular networks (TINs) and, subsequently, to calculate slopes of each triangulated segment of land surface. This process helped smooth out areas with relatively minor elevation variability across very small distances that otherwise complicated the interpretation of migration paths. Unfortu-

Table 1. *Land-use categories from 2005 aerial photography (MassGIS) classified as either softscape (<50% impervious surface; suitable for migration) or hardscape (>50% impervious surface; unsuitable for migration).*

| Softscape | Hardscape |
|---|---|
| Brushland/Successional | Commercial |
| Cranberry bog | High-density residential |
| Cropland | Marina |
| Forest | Medium-density residential |
| Forested wetland | Multifamily residential |
| Golf course | Transportation |
| Low-density residential | Urban public/institutional |
| Nonforested wetland | Roads |
| Open land | Riprap |
| Participation recreation | Impervious surface |
| Pasture | |
| Saltwater sandy beach | |
| Saltwater wetland | |
| Very low density residential | |

nately, there are scant published studies on threshold slope values that might impede migration or on whether the constraints of slope are due to the direct relationship between slope and horizontal distance or the indirect effect of slope on certain physicochemical gradients mentioned earlier (or both). In general terms, Kirwan *et al*. (2016) classified upland slopes of 0.1% as gentle, 1% as moderate, and 20% as severe, with the latter two categories resulting in high probabilities of net marsh loss during SLR. Similarly, Schieder (2017) found that, as upland slopes approach 2%, migration rate significantly decreases in salt marshes of the Chesapeake Bay region. Torio and Chmura (2013) developed a Coastal Squeeze Index, in which migration potential decreases exponentially at slopes above ~7–8%. In this analysis, two slope categories were included in the various migration scenarios, corresponding to 1% or 5% inclines, which are in the range of what others have considered limiting to migration (Brinson, Christian, and Blum, 1995; Kirwan *et al*., 2016; Schieder, 2017; Torio and Chmura, 2013).

Finally, the effects of barrier beach losses on PMAs were assessed. Barrier beaches are narrow projections of land oriented roughly parallel to the shoreline that provide sheltered environments conducive to the establishment of salt marsh vegetation. All the marshes analyzed in this study were located behind these landforms, which may deteriorate or disappear with accelerating SLR and storm intensity and/or frequency (FitzGerald *et al*., 2008; Gutierrez *et al.,* 2007; Leatherman, Zhang, and Douglas, 2000; Lorenzo-Trueba and Ashton, 2014; Moore *et al*., 2010; Williams, 2013; Zhang, Douglas, and Leatherman, 2004).

### Estimation of Net Changes in Salt Marsh Habitat

Responses of CCNS salt marshes to 1-m of SLR were previously estimated for HH, WE, GU, and PB within their present-day footprints, based on 2013 satellite imagery (Smith *et al*., 2016). This work was done by collecting a spatially dense array of marsh-surface elevation data for each site with RTK GPS with a vertical accuracy of ±2 cm (Feng and Wang, 2008). These data were interpolated to create digital elevation models in ArcGIS and were combined with tidal data, vegetation composition, elevation change rates from SETs, and published relationships between salt marsh plant productivity and elevation to develop a model of marsh responses to SLR (further details provided in Smith *et al.,* 2016). In addition, CCNS salt marsh habitat was previously mapped and described in Smith (2015a). Because there are fairly steep slopes along the upper edges of many CCNS marshes, transitions between the upper salt marsh and terrestrial vegetation tend to be abrupt and easily delineated. Along with the imagery, delineations of these landward borders were informed by hydrology and vegetation data from ground-level monitoring plots (Smith 2015a,b; Smith *et al*., 2016). With respect to tidal flooding, the landward border of high-marsh vegetation in southern New England conforms very well to mean highest high-water levels (MHHW) (Bertness and Ellison, 1987; Donnelly, 2006; Kemp *et al*., 2012, 2015; Nikitina *et al*., 2015).

Changes in MM were estimated by the same method as that used in Smith *et al*. (2016), but with SET data from nearby GU, which is ~1.8 km away and on the same landform and embayment (Great Island Peninsula, Wellfleet, Massachusetts). Changes in NS salt marsh area were determined with newly acquired elevation data since the Smith *et al*. (2016) study. The model could not be run for JM because there was insufficient elevation data to produce an accurate DEM. Net change in salt marsh area was calculated as *Present-day marsh area − Losses due to SLR with present-day footprint + Expansion due to migration*. Percentage of change in marsh areas was based on comparisons of estimated marsh area after 1-m of SLR from their present-day footprints. Additional scenarios excluded barrier beach areas, which could eventually be lost to SLR (Dubois, 1990; Leatherman, Zhang, and Douglas, 2000; Mellett and Plater, 2018; Moore *et al*., 2010). In summary, the following sets of conditions were analyzed: (1) unconstrained migration (no slope of land-use constraints), (2) migration constrained by land-use only (no slope constraints), (3) migration constrained to softscape and slopes ≤5%, (4) migration constrained to softscape and slopes ≤1%, and (5) all of the above conditions, excluding potential migration opportunities onto barrier beaches (*i.e*., simulated loss of those features).

## RESULTS

PMAs by site and the effect of migration constraints, including loss of barrier beaches, are summarized in Table 2. Table 3 illustrates net areal, and percentage of, gains/losses of salt marsh among the different migration scenarios during 1-m of SLR. With unconstrained migration, PMAs ranged between 1.5 ha (JM) and 250 ha (HH) and diminished only slightly with land-use and slope constraints until the latter was set to ≤1%. Although HH provided the largest area for expansion, there were abundant opportunities at PB (between 33 and 104 ha) as well. Losses of barrier beaches only slightly reduced PMAs at most sites, except PB, where it was reduced between twofold and fivefold (Table 2). Figure 2 illustrates patterns of marsh loss and unconstrained migration at individual sites.

Where constrained by both land-use and slopes, marsh migration opportunities were variably reduced among sites (Table 3). With slopes ≤5% and migration constrained to softscape, ~~the values for net marsh change with 1-m of SLR all~~

Table 2. *Present-day salt marsh areas, losses, and potential migration area (PMA) following 1-m of SLR in unconstrained, land-use constrained, and land-use/slope constraints. All values are in hectares. Highlighted columns of results are estimates that exclude barrier beaches (–bb) (HH = Hatches Harbor, WE = West End, GU = Gut, MM = Middle Meadow, JM = Jeremy, NS = Nauset, and PB = Pleasant Bay).*

| Site | | | no constraints | | land-use | | land-use/slopes ≤5% | | Land-use/slopes ≤1% | |
|---|---|---|---|---|---|---|---|---|---|---|
| | present area | loss-SLR | PMA | PMA-bb | PMA | PMA-bb | PMA | PMA-bb | PMA | PMA-bb |
| GU | 18.1 | 3.5 | 2.5 | 1.1 | 2.5 | 1.1 | 2.1 | 0.8 | 0.4 | 0.0 |
| HH | 66.6 | 9.4 | 250.0 | 250.0 | 250.0 | 250.0 | 247.5 | 247.5 | 153.8 | 153.8 |
| JM | 4.3 | 0.9 | 1.5 | 1.0 | 1.5 | 1.0 | 1.4 | 0.9 | 0.3 | 0.2 |
| MM | 22.5 | 2.7 | 2.4 | 1.4 | 2.4 | 1.4 | 2.2 | 1.2 | 0.3 | 0.3 |
| NS | 295.4 | 292.4 | 32.1 | 28.3 | 30.8 | 27.0 | 29.2 | 25.4 | 3.9 | 3.0 |
| PB | 388.4 | 24.1 | 104.4 | 52.1 | 104.4 | 51.2 | 96.8 | 44.2 | 32.6 | 6.5 |
| WE | 61.9 | 18.6 | 9.6 | 7.5 | 9.6 | 7.5 | 9.0 | 7.1 | 1.4 | 1.3 |
| All | 857.2 | 351.5 | 402.4 | 349.4 | 401.1 | 348.4 | 388.2 | 335.5 | 192.6 | 166.5 |

~~declined, although~~ there were still large expansions at both HH (+238 ha) and PB (+73 ha) and widespread losses at NS (–263 ha). GU, MM, and WE exhibited minor net losses of between 0.5 and 10 ha (–2% to –12%), whereas JM expanded by 0.5 ha (+12%). When migration was constrained to ≤1% slopes, marshes were markedly diminished in size with total losses (all sites) of 159 ha (–19%).

Loss of barrier beaches affected PB to the greatest degree (Table 3). Under land-use and ≤5% slope constraints, MM, NS, and WE changed very little (–1% to –5%) when barrier beach areas were removed, whereas JM was reduced by 12%. HH was not affected by barrier beach disappearance because there are essentially no habitable areas along the narrow, shifting sand spit that borders the main inlet. When constrained by land-use and ≤1% slopes, the degree of marsh migration reduced by barrier beach exclusion was very low (0–7% loss) (Table 3).

Although the total amount of salt marsh after 1-m of SLR remained relatively similar under most scenarios, it encompassed highly variable responses among individual sites (Tables 2 and 3). The most dramatic changes are predicted to occur at NS, where virtually all existing marsh island habitat may succumb to flooding, leaving only a narrow band of marsh around the periphery of the embayment. However, there are abundant opportunities for marsh expansion at HH, and that almost fully offsets marsh losses in every scenario, except where migration is constrained by land-use and ≤1% slopes, which results in decline of 159 ha (19% loss) or 185 ha (22% loss) without barrier beach habitat (Table 3). In essence, the total amount of salt marsh may be roughly similar or possibly greater as a consequence of 1-m of SLR, but the resource may be more spatially concentrated in certain areas of the park (such as in HH). Thus, although overall population size is maintained, the number of geographically distinct populations may ultimately be ~~greatly~~ reduced.

Table 3. *Estimates of net area change (Δ area; ha) and percentage of change (from present-day footprint) in CCNS salt marshes following 1-m of SLR based on unconstrained, land-use constrained, and land-use/slope constraints to migration. Highlighted columns represent scenarios in which barrier beaches are excluded (–bb) (Δ = net change; HH = Hatches Harbor, WE = West End, GU = Gut, MM = Middle Meadow, JM = Jeremy, NS = Nauset, and PB = Pleasant Bay).*

| | no constraints | | | | land-use | | | |
|---|---|---|---|---|---|---|---|---|
| Site | Δ area | Δ area-bb | %Δ | %Δ-bb | Δ area | Δ area-bb | %Δ | %Δ-bb |
| GU | -1.0 | -2.4 | -6% | -13% | -1.0 | -2.4 | -6% | -13% |
| HH | 240.6 | 240.6 | 361% | 361% | 240.6 | 240.6 | 361% | 361% |
| JM | 0.6 | 0.1 | 14% | 2% | 0.6 | 0.1 | 14% | 2% |
| MM | -0.3 | -1.3 | -2% | -6% | -0.3 | -1.3 | -2% | -6% |
| NS | -260.3 | -264.1 | -88% | -89% | -261.6 | -265.4 | -89% | -90% |
| PB | 80.4 | 28.1 | 21% | 7% | 80.4 | 27.2 | 21% | 7% |
| WE | -9.0 | -11.1 | -14% | -18% | -9.0 | -11.1 | -14% | -18% |
| All | 50.9 | -2.1 | 6% | 0% | 49.6 | -3.1 | 6% | 0% |

| | land-use/slopes ≤ 5% | | | | land-use/slopes ≤ 1% | | | |
|---|---|---|---|---|---|---|---|---|
| | Δ area | Δ area-BB | %Δ | %Δ-BB | Δ area | Δ area-BB | %Δ | %Δ-BB |
| GU | -1.4 | -2.7 | -8% | -15% | -3.2 | -3.5 | -18% | -19% |
| HH | 238.1 | 238.1 | 357% | 357% | 144.4 | 144.4 | 217% | 217% |
| JM | 0.5 | 0.0 | 12% | 0% | -0.6 | -0.6 | -14% | -15% |
| MM | -0.5 | -1.5 | -2% | -7% | -2.4 | -2.4 | -11% | -11% |
| NS | -263.2 | -267.0 | -89% | -90% | -288.5 | -289.4 | -98% | -98% |
| PB | 72.8 | 20.2 | 19% | 5% | 8.6 | -17.5 | 2% | -5% |
| WE | -9.6 | -11.5 | -15% | -19% | -17.2 | -17.3 | -28% | -28% |
| All | 36.7 | -16.0 | 4% | -2% | -159.0 | -185.1 | -19% | -22% |

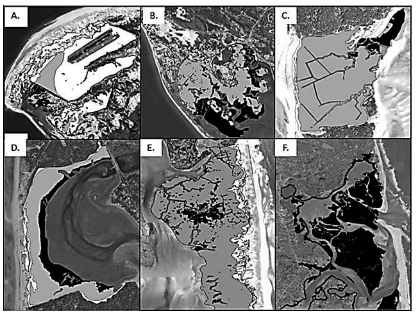

Figure 2. Estimations of marsh changes without land-use or slope constraints in a 1-m SLR scenario. Black polygons are marshes that have been lost, gray polygons are present-day marshes, and white polygons are potential marsh habitats with landward migration. A = Hatches Harbor, B = West End, C = Middle Meadow, D = Gut, E = Pleasant Bay, F = Nauset; PB and NS figures show only portions of those systems to provide adequate resolution).

## DISCUSSION

Rates of SLR around the Cape Cod peninsula are currently higher than ~~vertical~~ elevation gain, and a global rise in sea-level of 1 m is expected to produce even higher increases in sea level along the coastline of southern New England. In fact, 1.13 m of SLR is predicted at Falmouth, 1.10 m at Buzzard's Bay, and 1.11 m at Sandwich, Massachusetts (data available at Jetstream, 2019) (Sweet *et al.*, 2017). Thus, estimates of marsh losses and gains in this study are actually quite conservative and probably represent the least amount of change that would occur.

With exactly 1-m of SLR at CCNS, most marshes are predicted to experience slight gains or losses in the absence of any land-use or slope limitations on landward migration. The notable exceptions to this are at NS, where there may be a major collapse of large marsh islands, and at HH, where marshes could expand far into the dunes. Unfortunately, a relatively small percentage of loss within any marsh footprint can equate to meaningful losses of important habitat, upon which, myriad organisms depend (Boesch and Turner, 1984; Teal, 1962). For example, a 14% reduction at WE in an unconstrained migration scenario equates to a 9-ha loss of habitat. Although this may be trivial from the standpoint of its effect on total salt marsh acreage, it would directly affect organisms inhabiting and/or using that particular system. Moreover, net losses of salt marsh at individual sites will ~~directly~~ affect carbon sequestration in these systems. Carbon stocks in the NE United States salt marsh ecosystems range between 400 and 1,500 kg/ha (Drake *et al*., 2015). Using a midpoint value of 950 kg/ha, therefore, NS would lose $\sim 2.8 \times 10^6$ metric tons of carbon with a 1-m rise in sea level. CCNS marsh losses may further affect adjacent ecosystems (*e.g*., seagrass meadows) with which they are closely tied (Craft *et al*., 2009; Reed, 1990).

It is safe to assume that migration will be impeded by human infrastructure on some level, and it noteworthy that the footprint of human development has increased both inside and outside the park since the land-use map used in this study was created in 2005. Nevertheless, land-use did not prove to be a ~~very significant~~ constraint for 1-m of SLR, mainly because (1) only NS and PB embayment have extensively developed uplands surrounding marsh habitat, and (2) a 1-m rise will not be sufficient to inundate much of the infrastructure (homes, driveways, roads, *etc*.), which is ~~typical~~ set back at a distance from marsh edges. With respect to the latter, a 2-m rise in sea-level will flood far more of the terrestrial landscape, and land-use will consequently have ~~proportionally~~ larger effects on migration patterns. This result is due to the steeper slopes around the margins of CCNS salt marshes. On other parts of the peninsula in which surrounding uplands are flatter and more gently sloped from the marsh edge (and in flatter coastal states where this is also the case), land-use will figure much more prominently under a 1-m SLR scenario. In addition, some steep-sided dunes will ~~undoubtedly~~ become increasingly level with erosion (especially during storm events) to create conditions more suitable for upslope migration. By contrast, there may be relatively little topographic change in newly flooded forest habitat because the ground is so highly stabilized by its extensive root systems.

Salt marsh migration is regulated both separately and synergistically by salinity and inundation conditions (Kirwan and Gedan, 2019), which vary spatially and temporally along the terrestrial borders of salt marshes. As such, change occurs in a more punctuated fashion in which transition zones between salt marsh and terrestrial habitats fluctuate rapidly, followed by periods of relative stability until the next big shift (Brinson, Christian, and Blum, 1995; Enwright, Griffith, and Osland, 2016; Fagherazzi *et al*., 2019; Kirwan and Gedan, 2019; Kirwan and Murray, 2008; Koppel *et al*., 2004; Leonardi and Fagherazzi, 2015; Marani *et al*., 2010). Occasionally, tree regeneration will fail before mature tree death occurs (Clark, 1986; Conner and Day, 1988; Williams *et al*., 1999) or thinning of the forest canopy occurs before marsh plants colonize the site (Brinson, Christian, and Blum, 1995; Langston *et al*., 2017; Williams *et al*., 1999). Field, Gjerdrum, and Elphick (2016) found that, although high marsh was disappearing in Connecticut because of SLR, there was relatively low mortality and high growth rates in vegetation (mostly trees) at the upper marsh edge and, hence, no discernible forest retreat. ~~In other words, the effects of SLR all occurred in the high-marsh zone.~~ Alternatively, salinity and flooding can cause rapid and widespread tree mortality and the development of "ghost forests" as described in Kirwan and Gedan (2019).

Lateral erosion is another process that will influence whether marshes exhibit net expansion or contraction (Kirwan *et al*., 2016). The dynamics of marsh-edge erosion are complex (Marani *et al*. 2011 and references therein), however, and depend on numerous site-specific parameters, such as hydrology, fetch, tidal volumes/velocities, nearshore bathymetry, top-down consumer pressure, soil infauna, trophic state, geomorphology, soil structure, elevation, vegetation types, and local ocean conditions, including wave height/direction, rate of SLR, storm frequency, and overwash events, *etc*. On Cape Cod, marsh-edge retreat mediated by physical processes is most conspicuous in places in which a tidal inlet has shifted in a way that directs incoming seawater flow toward a new portion of marsh (Smith, 2009). There are other areas of narrow, fringing marshes without the protection of a barrier beach (*e.g*., along Cape Cod Bay) in which wave-driven erosion is obvious, and a form of chemical erosion (hydrogen sulfide toxicity) around tide pool edges at NS has caused those features to expand (Erwin *et al*., 2006). Otherwise, the spatial scale of erosive losses appears to range from centimeters to several meters (at least during recent decades), and this may be confounded by errors associated with image georeferencing and/or the resolution of the imagery itself, which is generally poorer in older photography. It also may be the case that seaward-edge erosion at CCNS is not currently as influential as increased flooding frequencies across whole systems, which have resulted in dramatic shifts from high- to low-marsh vegetation (Smith 2015a). In other words, flooding conditions at the lowest elevations in which *S. alterniflora* occurs in most CCNS marshes may still be within, or close to within, the physiological tolerance range for this species in these particular soils. In the future, lateral erosion may become more important as the marshes sink lower in their tidal frames, embayments deepen, and barrier beaches degrade.

Other aspects of climate change not addressed in this analysis may further affect marsh migration patterns. Increased rainfall influences competitive interactions between halophytes and terrestrial species through alterations to root-zone salinity gradients. In areas of greater groundwater inputs, forest retreat tends to be lower because of the depression of root-zone salinities (Raabe and Stumpf, 2016). Interannual variability in mean sea level, which results from shifts in prevailing atmospheric and oceanographic circulation patterns (Goddard *et al*., 2015; Kemp *et al*., 2015; McCarthy *et al*., 2015; Sallenger, Doran, and Howd, 2012), may also have a role in marsh–upland vegetation dynamics. Storm events deliver pulses of seawater that penetrate into the upland and sometimes persist for several tidal cycles. Such events can kill salt-intolerant terrestrial vegetation, and the standing dead material then acts as a physical barrier to halophyte seed dispersal (Smith, 2007). Lastly, disparities in the rates of water level increases for specific tidal variables may be important in salt marsh–terrestrial interactions, particularly where mean high tide is rising faster than mean sea level, such as in the Gulf of Maine (Flick, Murray, and Ewing, 2003).

A weakness of this analysis stems from the difficulty of predicting barrier beach dynamics with SLR given that there

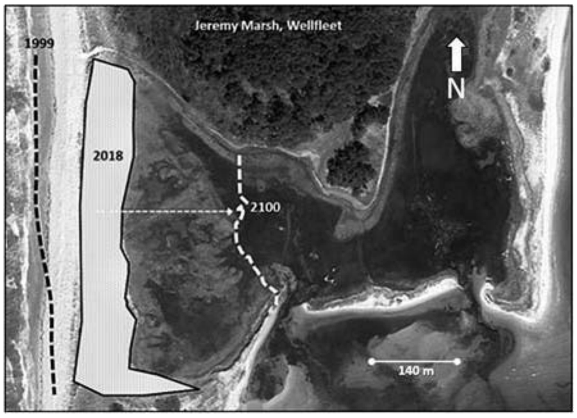

Figure 3. Aerial photography of JM showing the 1999 (dotted black line) *vs.* 2018 bluff edges and the migration of dunes eastward onto the marsh. Also noted is the predicted bluff edge position in 2100 (white dotted line) given the same rate of bluff movement that has occurred over the past 30 years (~1 m/y).

are myriad factors (friction, elevation, *etc.*) that can influence their fate (Mickey *et al.*, 2017; Passeri *et al.*, 2018). It would be particularly useful to understand how barrier beach transgression relates to sediment deposition over marshes for varying intensities of storms (Mickey *et al.*, 2017). A significant narrowing or a complete disintegration of barrier beaches can occur (and has occurred in many places), especially where SLR outpaces sediment supply (Zhang, Douglas, and Leatherman, 2004). In a scenario where barrier beaches are eliminated completely, the amount of landward migration that could occur would be variably but markedly reduced in some marshes, such as PB. During the past several decades, erosion rates from the outer Cape Cod range of ~0.4 m/y (Maio *et al.*, 2014) to 1.5 m/y (Leatherman and Zaremba, 1986). This agrees very well with the U.S. Geological Survey (USGS) assessment of long-term shoreline change rates of ~0.4 m/y and 0.9 m/y along the Cape Cod Bay and Atlantic coastlines, respectively (USGS, 2019). At current rates of barrier beach retreat, salt marsh vegetation migration areas onto these landforms will be extremely limited or nonexistent (Deaton, Hein, and Kirway, 2017). In some cases, sand blowing over the top of the bluff, which, in minor amounts, can facilitate elevation gain and marsh persistence, can kill plants if ≥10 cm of material is deposited (Walters and Kirwan, 2016). The latter is what has occurred in some areas, such as JM, in which shoreline retreat has already buried a considerable portion of the marsh during the past few decades (Figure 3). That said, the only evidence of this burial process occurring to any significant extent is along certain portions of marshes on the Great Island peninsula in Wellfleet (GU, MM, and JM).

The losses predicted for NS island marshes may be due to its elevation relative to its tidal range. In this system, which is dominated by large, isolated islands, ~~and~~ the lowest elevations where *S. alterniflora* occurs is considerably higher than at all other sites (data from Smith *et al.,* 2016). That is, the growth range of *S. alterniflora* at NS is narrow and displaced upward, with the lower limit of marsh vegetation occurring above the mean low tide (MLT). In contrast, lower limits fall well below the MLT elevations at all other sites (Figure 4). Such variations in elevation ranges have been previously documented by McKee and Patrick (1988) who contended that lower limits generally extend further seaward (downslope) with increasing tidal range and *vice versa*. Because the tidal range at NS is fully 1-m ~~lower~~ than at all other sites, much more of the *S. alterniflora* growth range at NS will be inundated for a given rise in sea level, and that renders NS or any salt marsh in similar conditions more susceptible to increased flooding (Kirwan and Guntenspergen, 2010). NS marsh islands also consist of deep peat layers, have vertical edges, and are not connected to any land mass. Hence, vegetation cannot move up an elevation gradient. The highly organic content of NS soils and mudflats may further preclude vegetation growth at lower elevations (van Wesenbeeck *et al.*, 2007) because the soils in most other CCNS marshes comprise mainly sand and, therefore, experience less anoxia and hydrogen sulfide production. This stress may already be manifested in the low, aboveground and total biomass of NS vegetation compared with other marshes (Smith, 2015b).

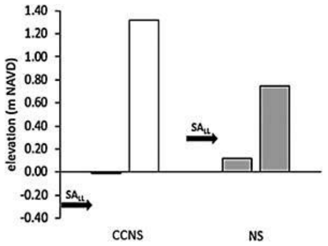

Figure 4. Elevations of mean tide heights (MTH) *vs.* lower limits of *S. alterniflora* ($SA_{LL}$) in Nauset (NS) *vs.* the average of all other marshes (CCNS) (lower limits and tide heights are from Smith *et al.* 2016).

## CONCLUSIONS

Coastal land managers are looking for ways to preserve the range and magnitude of ecosystem services that salt marshes provide as rising sea levels threaten their integrity (Borchert *et al.*, 2018). Assessments of overland migration potential and limitations on the process can help inform decision-making by coastal managers on prioritizing protection/restoration efforts. The possibility of a massive collapse of marsh islands in NS is an important finding of this analysis, and direct restoration, such as thin-layer deposition, may have to be considered in the future (Ford, Cahoon, and Lynch, 1999). Likewise, the potential for significant increases in salt marsh at HH will require infrastructure planning around park roads and the Provincetown airport to accommodate that transition, especially because that site may be the only area to experience large gains in a way that would preserve as much total marsh habitat as possible within CCNS.

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