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Barrier island migration dominates ecogeomorphic feedbacks and drives salt marsh loss along the Virginia Atlantic Coast, USA

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SUPPLEMENTAL MATERIALS

1. Supplemental Methods

Historical backbarrier marsh and open-water areas along the Virginia barrier islands were derived through digitizing the marsh-water boundary at map scale (1:20,000) from a series NOS T-sheets. A list of T-sheets used are provided in Table DR1.

Errors in shoreline movement rates were determined similarly to Hapke et al. (2011). The uncertainty of each mapped shoreline was input to the Digital Shoreline Analysis System (DSAS: Thieler et al., 2008), which returned a linear regression along each transect (50 meter spacing), and also provided a 2σ (95.5%) confidence interval calculated from each shoreline's uncertainty value. Island uncertainties were calculated as the average uncertainty of each transect crossing an island, divided by the number of transects. This method of calculating island-averaged uncertainty assumes that each transect uncertainty is independent of all other transects, which is likely not a condition that is fully met by barrier island shorelines (Hapke et al., 2011). While our reported uncertainties are not especially conservative, we believe this approach to be superior to a simple regional average, as it captures the benefit of using multiple transects to improve the precision of shoreline movement rates.

Errors in marsh and open-water area mapping were calculated by obtaining the perimeter of all areas of marsh and water within each subdivision (bayshed, barriershed, or all islands) and multiplying that perimeter (or cross-sectional area, in the case of tidal prism) by the uncertainty introduced during mapping, after Hapke et al. (2011): +/- 11.7 m for T-sheets and +/- 5.5 m for aerial photographs. This returns the maximum amount of variation possible in mapping, making this a highly conservative estimation of mapping error. Uncertainty in changes in areal extent and tidal prism were calculated as the square root of the sum of squares of the T-sheet area/tidal prism and the corresponding 2009 value.

Tidal prism is alternately defined as the volume of water that moves through an inlet during an average flood or ebb stage of a tidal cycle, or as the difference in water volume in a tidal area (backbarrier, estuary, etc.) between high and low tide (Hume, 2005). For our analyses we define TP*, a proxy for tidal prism, as:

$$TP^* (m^3) = TR (m) * [Open\ Water\ Area (m^2) + (Intertidal\ Area (m^2) * k)] \quad (1)$$

where TR is the spring tidal range (1.4 m) and k is a geographically specific constant representing the proportion of each tidal cycle that the average intertidal area (salt marshes and tidal flats) is submerged, estimated at 0.15 based on marsh flooding frequencies from Walters and Kirwan (2016). Backbarrier marsh and open-water area errors were determined in the same manner as shoreline position error (i.e. perimeter multiplied by shoreline uncertainty) and propagated to TP* error.

Table DR1. Data sources for historical marsh and open-water areas along the Virginia Barrier Islands.

T-Sheet ID*	Year	Spatial Coverage
T00464	1854	Southern Metompkin Island and northern Cedar Island
T00492	1855	Wallops, Assawoman, and northern Metompkin Islands
T00509	1852	Smith, Myrtle, Ship Shoal, and southern Mockhorn Islands
T01200	1871	Hog, Parramore, and southern Cedar Islands
T01201	1869	Cobb Island
T1202B	1871	Ship Shoal, Wreck, and Mockhorn Islands (all partial coverage)
T1204	1871	Machipongo River
POG30-00-1895	1895	Mockhorn Island (Public Oyster Grant chart)

* - note that Table DR1 only contains data sources used to map marsh and open water areas. We direct the reader to Himmelstoss et al. (2010) for a list of the sources used in that study to compile the shoreline dataset (of which we used the “Delmarva south” portion in this study).

2. Supplemental Results and Discussion

2.1. Shoreline Retreat

Values for the long- (1850/1–2010) and short- (1850/1–1910/1; 1980–2010) term island-averaged and system-wide shoreline-retreat rates are provided in Table DR2.

Previous studies of shoreline change along the Virginia barrier islands works have spanned from high-resolution investigations of changes along individual islands within the system (*e.g.,* Fenster and Dolan, 1996; Fenster and Hayden, 2007; Richardson, 2012; Richardson and McBride, 2007, 2011; Nebel et al., 2012; McBride et al., 2015; Richardson et al., 2015), to larger-scale studies of the entire barrier system (Rice et al., 1976; Dolan et al., 1979), to integrative investigation of the southern Delmarva Peninsula as a whole (Hapke et al., 2011). Our results compare favorably with these (Table DR3).

For example, our data indicate that the average system-wide (Metompkin to Smith islands) shoreline-retreat rate in the period of 1850/1 to 2010 5.1 m yr^{-1} (Table DR2). This is consistent with system-wide 20th century estimates of *ca.* 5 m yr^{-1} (Leatherman et al., 1982). More recent estimates (Hapke et al., 2011, 2013) are lower (2.9 m $yr^{-1;}$ 1850s–1997). This same mis-match is observed in the short-term shoreline-change rates: average system-wide short-term shoreline retreat was determined here to be 7.0 m yr^{-1} but only 2.7 m yr^{-1} by Hapke et al. (2011, 2013). It is noted that the "short-term" rates of Hapke et al. (2011, 2013) covers an earlier period than our study and a different geographic range: the region studied by Hapke et al. (2011, 2013) incorporates both barrier islands and mainland beach (the former have experienced shoreline change rates of ~7x those of the latter), as well as the developed and largely stabilized shorelines of Wallops Island, Virginia outer coast south of the Chesapeake Bay mouth (*i.e.*, Virginia Beach and Sandbridge), and the accretionary Fisherman's Island immediately south of our study area (Figure 1a).

These differences in coverage are particularly critical in comparisons of short-term rates: an increase in short-term shoreline-change rates as compared to long-term rates has been well documented along much of the Delmarva Peninsula and the VBIs (Richardson and McBride, 2007, 2011; Nebel et al., 2012), particularly in the early 21st century (Richardson, 2012). This acceleration, observed for both our system-wide data and along most individual VBI (section 2.2.2), has been attributed to causes including impacts from more frequent tropical storm and hurricanes, updrift sediment trapping at Fishing Point on the southern end of Assateague Island, and acceleration in relative sea-level rise (Rice and Leatherman, 1983; Gaunt, 1991; Fenster et al., 1993; Richardson and McBride, 2007, 2011; Richardson, 2012; Nebel et al., 2012; McBride et al., 2015; Richardson et al., 2015). Thus, even in regions of overlap, the earlier timeframe captured in the "short-term" shoreline-change rates of Hapke et al. (2011, 2013) fails to capture the most recent 10 years of acceleration included in our much higher rate.

Table DR2. Long-term, short-term, and change in shoreline change rates for Virginia Barrier Islands.

Island	Long-Term (1851/2–2010) Barrier Retreat Rate (m yr^{-1})	Short-Term Early (1851/2–1910/1) Barrier Retreat Rate (m yr^{-1})†	Short-Term Recent (1980–2010) Barrier Retreat Rate (m yr^{-1})	Difference: Early to Late Barrier Retreat Rate (m yr^{-1})‡
Wallops*	0.5 ±0.01	-0.8 ±0.17	-10.4 ±0.34	-9.6 ±0.38
Assawoman*	3.6 ±0.09	0.2 ±0.84	4.0 ±0.19	3.8 ±0.86
Metompkin	6.2 ±0.03	3.6 ±0.03	10.9 ±1.03	7.3 ±1.03
Cedar	5.0 ±0.02	5.5 ±0.31	10.8 ±0.45	5.3 ±0.55
Parramore	4.5 ±0.02	-3.0 ±0.28	12.4 ±0.30	15.4 ±0.41
Hog	1.2 ±0.03	2.5 ±0.61	-1.3 ±0.32	-3.8 ±0.69
Cobb	2.1 ±0.04	10.2 ±3.56	3.2 ±2.59	-7.0 ±4.40
Wreck	4.9 ±0.16	16.8 ±0.03	4.2 ±1.00	-12.6 ±1.00
Ship Shoal	3.8 ±0.43	-3.2 ±2.50	6.0 ±4.75	9.2 ±5.36
Myrtle	6.0 ±0.12	9.7 ±0.77	19.3 ±5.67	9.6 ±5.72
Smith	5.7 ±0.01	5.2 ±0.08	2.8 ±0.33	-2.5 ±0.34
All VBIs	5.1 ±0.01	2.9 ±0.04	7.0 ±0.07	4.2 ±0.08

† - positive values indicate retreat (westward shoreline movement); negative values indicate advance (eastward shoreline movement)

‡ - positive values indicate acceleration in migration; negative values indicate deceleration

* - Wallops Island and part of Assawoman Island are artificially stabilized as part of NASA Wallops Flight Facility since at least 1945

2.2. Marsh, Open-Water, and Tidal Prism Changes

Values for barriershed-integrated historical (1870) and modern (2009) marsh, open-water, and backbarrier areas along the Virginia barrier islands are provided in Table DR4. Calculated historical and modern values for TP* are also provided, along with calculated changes in these values between historical and modern time periods. Finally, marsh area gain/loss in each of these systems are also provided in Table DR4 and presented visually for the entire Virginia barrier islands system in Figure DR1. These results are used as inputs for Figure 2 of the article and summarized and discussed in the main article body text. Table DR5 presents these same area and TP* changes, except separated by "bayshed" (approximate area flooded and drained by a given tidal inlet). Bayshed extents and changes in TP* for each bayshed (1870–2009) are shown in Figure DR1a.

Table DR3. Comparison of island-integrated shoreline retreat and/or advance rates from this study and earlier works. Positive values indicate retreat (westward shoreline movement); negative values indicate advance (eastward shoreline movement). Shoreline-change rates are only provided if given as island-wide rates in original studies.

Island	Time period covered	Length of Record (yrs)	Description of length	Rate	Source
Wallops	1852–1974	122	Long-term early	1.5	Dolan et al., 1979
	1852–1974	122	Long-term early	2.0	Leatherman et al., 1982
	1852–2010	158	Long-term	0.5 ± 0.01	this study
	1852–1910	58	Short-term early	-0.8 ± 0.17	this study
	1980–2010	30	Short-term recent	-10.4 ± 0.34	this study
Assawoman	1852–1974	122	Long-term early	3.1	Dolan et al., 1979
	1852–1974	122	Long-term early	3.5	Leatherman et al., 1982
	1852–2010	158	Long-term	3.6 ± 0.09	this study
	1852–1910	58	Short-term early	0.2 ± 0.84	this study
	1980–2010	30	Short-term recent	4.0 ± 0.19	this study
Metompkin	1852–1955	103	Long-term early	4.7	Rice et al., 1976
	1852–1974	122	Long-term early	6.9	Dolan et al., 1979
	1852–1974	122	Long-term early	5.0	Leatherman et al., 1982
	1852–2010	158	Long-term	6.2 ± 0.03	this study
	1852–1910	58	Short-term early	3.6 ± 0.03	this study
	1955–1968	13	Short-term intermediate	5.4	Rice et al., 1976
	1980–2010	30	Short-term recent	10.9 ± 1.03	this study
Cedar	1852–1968	116	Long-term early	5.1	Rice et al., 1976
	1852–1974	122	Long-term early	3.9	Dolan et al., 1979
	1852–1974	122	Long-term early	4.9	Leatherman et al., 1982
	1852–2007	155	Long-term	5.5 ± 0.1	Richardson, 2012; Richardson and McBride, 2011
	1852–2007	155	Long-term	4.1	Nebel et al., 2012
	1852–2010	158	Long-term	5.0 ± 0.02	this study
	1852–2010	158	Long-term	6.1	Richardson, 2012
	1852–1910	58	Short-term early	5.5 ± 0.31	this study
	1910–1962	52	Short-term intermediate	3.0	Nebel et al., 2012
	1910–1986	76	Short-term intermediate	4.4	Gaunt, 1991
	1962–2007	45	Short-term recent	7.2	Nebel et al., 2012
	1980–2010	30	Short-term recent	10.8 ± 0.45	this study
	1994–2007	13.0	Short-term recent	12.6	Nebel et al., 2012
	2007–2010	3	Short-term modern	15.4 ± 0.1	Richardson, 2012; Richardson and McBride, 2011
Parramore	1852–1974	122	Long-term early	4.5	Dolan et al., 1979
	1852–1998	146	Long-term	4.1	Richardson, 2012
	1852–2006	154	Long-term	3.6 ± 0.1	Richardson and McBride, 2007
	1852–2010	158	Long-term	4.5 ± 0.02	this study
	1852–2010	158	Long-term	5.0	Richardson, 2012

	1852–1910	58	Short-term early	-3.0 ± 0.28	this study
	1980–2010	30	Short-term recent	12.4 ± 0.30	this study
	1998–2006	8	Short-term recent	8.8 ± 0.1	Richardson and McBride, 2007
	1998–2010	12	Short-term recent	12.2 ± 0.1	Richardson, 2012
Hog	1852–1974	122	Long-term early	6.5	Dolan et al., 1979
	1852–2010	158	Long-term	1.2 ± 0.03	this study
	1852–1910	58	Short-term early	2.5 ± 0.61	this study
	1980–2010	30	Short-term recent	-1.3 ± 0.32	this study
Cobb	1852–1962	110	Long-term early	2.5–2.7	Rice et al., 1976
	1852–1974	122	Long-term early	2.5	Dolan et al., 1979
	unknown	150 (?)	Long-term	3–6	Oertel et al., 1989
	1852–2010	158	Long-term	2.1 ± 0.04	this study
	1852–1910	58	Short-term early	10.2 ± 3.56	this study
	1980–2010	30	Short-term recent	3.2 ± 2.59	this study
Wreck	1852–1974	122	Long-term early	2.0	Dolan et al., 1979
	1851–2010	159	Long-term	4.9 ± 0.16	this study
	1851–1910	59	Short-term early	16.8 ± 0.03	this study
	1980–2010	30	Short-term recent	4.2 ± 1.00	this study
Ship Shoal	1852–1974	122	Long-term early	-1.7	Dolan et al., 1979
	1852–1974	122	Long-term early	5.5	Rice et al., 1976
	1851–2010	159	Long-term	3.8 ± 0.43	this study
	1851–1910	59	Short-term early	-3.2 ± 2.50	this study
	1980–2010	30	Short-term recent	6.0 ± 4.75	this study
Myrtle	1852–1974	122	Long-term early	1.0	Dolan et al., 1979
	1851–2010	159	Long-term	6.0 ± 0.12	this study
	1851–1910	59	Short-term early	9.7 ± 0.77	this study
	1980–2010	30	Short-term recent	19.3 ± 5.67	this study
Smith	1852–1974	122	Long-term early	3.3	Dolan et al., 1979
	1853–1974	121	Long-term early	4.3–7.5	Rice et al., 1976
	1851–2010	159	Long-term	5.7 ± 0.01	this study
	1851–1910	59	Short-term early	5.2 ± 0.08	this study
	1980–2010	30	Short-term recent	2.8 ± 0.33	this study
All VBIs	1851–2010	159	Long-term	5.1 ± 0.01	this study
	1851–1910	59	Short-term early	2.9 ± 0.04	this study
	1980–2010	30	Short-term recent	7.0 ± 0.07	this study
Southern Delmarva & Southern Virginia*	1850s–1997/2000	~150	Long-term	2.9	Hapke et al., 2010, 2013
	1960/70s–1997/2000	~30	Short-term recent	2.7	Hapke et al., 2010, 2013

* - note: includes artificially stabilized Virginia Beach area

Table DR4. Characteristics of backbarrier environments of Virginia barrier islands through time. Positive values indicate net gains. Note that "Marsh buried by barrier (for a given island)" refers to marsh buried by the migration of a single island, whereas "Barriershed marsh buried by barrier" refers to the amount of marsh buried within an island's barriershed, which is defined as the sum of the two baysheds (Table DR5) bounding each island, and therefore includes marsh buried on adjacent islands.

Barrier Island	**1870 Barriershed Water Area (km^2)**	**1870 Barriershed Marsh Area (km^2)**	**1870 Total Barriershed Area (km^2)**	**2009 Barriershed Water Area (km^2)**	**2009 Barriershed Marsh Area (km^2)**	**2009 Total Barriershed Area (km^2)**	**Change in Marsh Area (km^2)**	**Change in Water Area (km^2)**	**Change in total back-barrier area (km^2)**
Metompkin	31.5 ±4.5	46.3 ±2.5	77.7 ±2.5	22.3 ±1.8	34.8 ±1.1	57.1 ±1.1	-11.4 ±4.9	-9.2 ±2.7	-20.6 ±2.7
Cedar	64.4 ±5.5	77.3 ±3.5	141.7 ±2.5	63.0 ±2.4	66.2 ±1.6	129.2 ±1.2	-11.1 ±6.0	-1.4 ±3.8	-12.5 ±2.8
Parramore	98.9 ±5.2	97.3 ±4.5	196.2 ±1.5	112.4 ±2.4	84.0 ±2.0	196.4 ±0.9	-13.3 ±5.7	13.5 ±5.0	0.2 ±1.8
Hog	202.6 ±6.5	98.5 ±5.2	301.1 ±2.4	215.3 ±2.9	81.6 ±2.2	296.9 ±1.3	-16.9 ±7.2	12.7 ±5.6	-4.2 ±2.8
Cobb	227.1 ±7.2	115.3 ±5.6	342.4 ±2.8	245.3 ±3.2	87.2 ±2.4	332.4 ±1.5	-28.1 ±7.9	18.2 ±6.1	-10 ±3.2
Wreck	98.3 ±3.6	70.8 ±2.9	169.0 ±1.2	109.7 ±1.5	46.5 ±1.2	156.2 ±0.6	-24.2 ±3.9	11.4 ±3.2	-12.8 ±1.3
Ship Shoal	34.8 ±1.7	40.9 ±1.5	75.6 ±0.6	33.3 ±0.6	31.4 ±0.5	64.7 ±0.3	-9.5 ±1.8	-1.5 ±1.6	-10.9 ±0.6
Myrtle	27.7 ±1.7	35.2 ±1.6	62.9 ±0.5	19.8 ±0.5	33.1 ±0.4	52.9 ±0.2	-2.0 ±1.8	-7.9 ±1.7	-9.9 ±0.5
Smith	56.1 ±2.5	26.7 ±1.6	82.8 ±1.3	44.3 ±1.0	26.2 ±0.6	70.5 ±0.5	-0.5 ±2.7	-11.8 ±1.8	-12.3 ±1.4
All islands	448.3 ±20.6	326.5 ±15.1	774.8 ±7.1	457.0 ±8.6	264.0 ±6.3	721.0 ±3.5	-62.9 ±22.4	9.2 ±16.3	-53.7 ±8.0

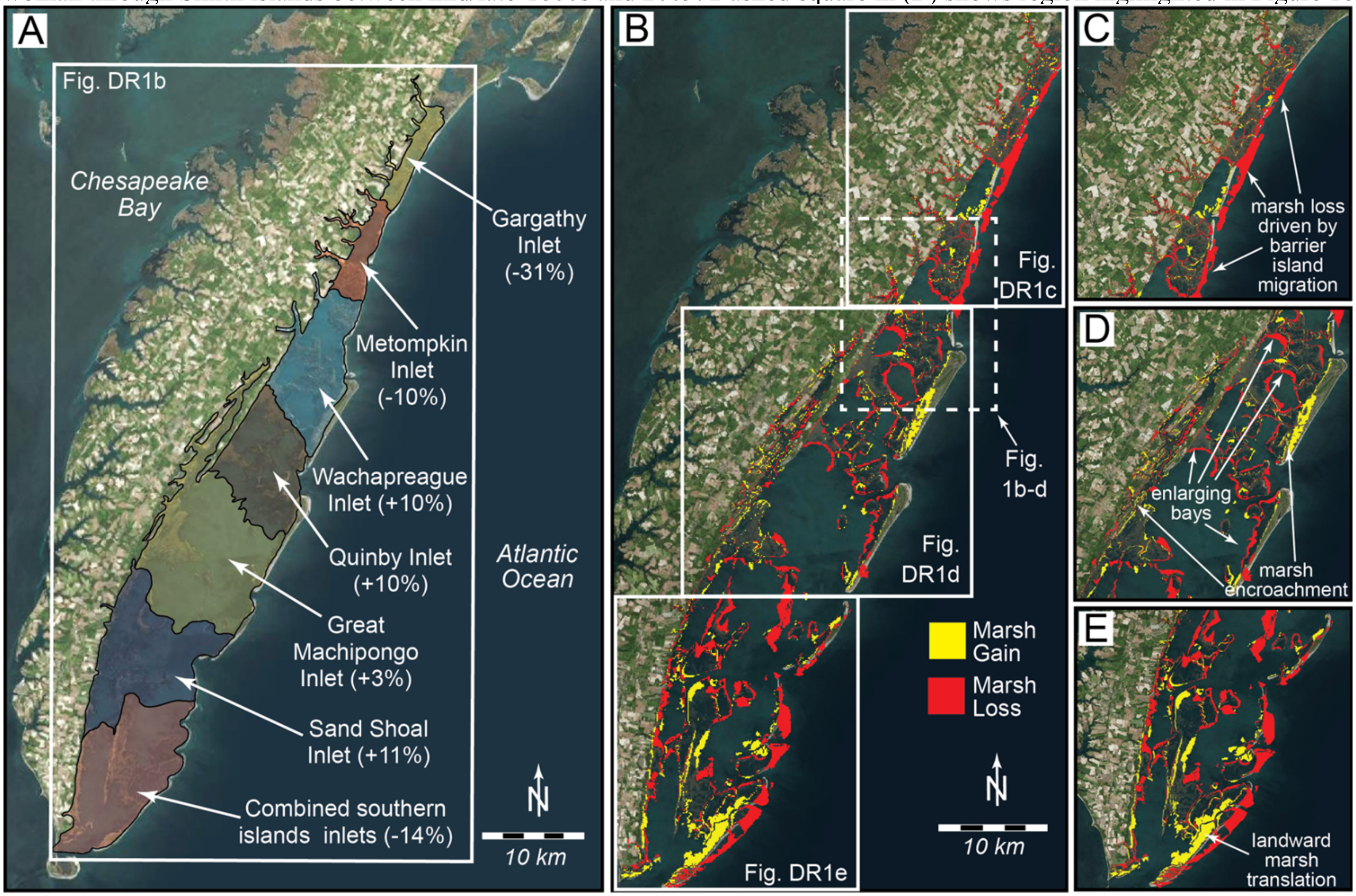
Table DR4 continued.

Barrier Island	**1870 TP* (x 10^6 m^3)**	**2009 TP* (x 10^6 m^3)**	**Δ TP* (x 10^6 m^3)**	**Marsh buried by barrier (for a given island) (km^2)**	**Barriershed marsh buried by barrier (km^2)**	**Barriershed Interior Marsh Change (km^2)**
Metompkin	53.8 ±4.4	38.5 ±1.9	-15.3 ±4.8	-7.9 ±0.6	-13.2 ±1.0	1.8 ±4.4
Cedar	106.4 ±6.0	102.1 ±2.7	-4.3 ±6.6	-4.9 ±0.4	-10.3 ±0.8	-0.8 ±5.6
Parramore	158.9 ±7.4	175 ±3.3	16.1 ±8.1	-0.1 ±0.0	-3.5 ±0.3	-9.9 ±5.7
Hog	304.4 ±8.6	318.6 ±3.7	14.2 ±9.4	-1.3 ±0.2	-1.7 ±0.4	-15.2 ±7.1
Cobb	342.2 ±9.4	361.7 ±4.1	19.5 ±10.2	-2.0 ±0.3	-4.3 ±0.6	-23.8 ±7.6
Wreck	152.4 ±4.8	163.3 ±2.1	10.9 ±5.3	-4.1 ±0.2	-5.0 ±0.6	-19.2 ±3.5
Ship Shoal	57.3 ±2.5	53.2 ±0.8	-4.1 ±2.6	-2.8 ±0.2	-6.5 ±0.5	-3.0 ±1.6
Myrtle	46.2 ±2.6	34.7 ±0.7	-11.5 ±2.7	-1.9 ±0.1	-6.4 ±0.4	4.4 ±1.6
Smith	84.1 ±2.8	67.5 ±1.1	-16.6 ±3.0	-7.3 ±0.8	-8.8 ±0.9	8.3 ±2.1
All islands	696.2 ±25.4	695.9 ±10.6	-0.3 ±27.6	-32.3 ±3.4	-32.3 ±3.4	-30.6 ±20.5

Table DR5. Characteristics of backbarrier environments of Virginia barrier islands separated by inlet bayshed (area drained by a given tidal inlet) through time. Positive values indicate net gains. Note that baysheds of southern four islands (Wreck, Myrtle, Ship Shoal, and Smith islands) are combined into a single bayshed for a more representative comparison to other baysheds.

Tidal Inlet	Associated barrier islands	Bayshed total marsh change (km^2)	Bayshed barrier-driven marsh change (km^2)	Bayshed interior marsh change (km^2)	1870 bayshed TP* ($\times 10^6$ m^3)	2009 bayshed TP* ($\times 10^6$ m^3)	Change in bayshed TP* ($\times 10^6$ m^3)	Change in bayshed TP* (%)
Gargathy Inlet	Assawoman-Metompkin	-6.8 ±2.3	-6.1 ±2.1	-0.7 ±1.0	17.2 ±2.2	13.4 ±1.0	-3.8 ±2.4	-22.2 ±14.0
Metompkin Inlet	Metompkin-Cedar	-4.6 ±2.7	-7.1 ±2.1	2.4 ±1.1	36.6 ±2.2	25.1 ±1.0	-11.5 ±2.4	-31.4 ±6.6
Wachapreague Inlet	Cedar-Parramore	-6.5 ±3.5	-3.2 ±0.2	-3.3 ±3.4	69.8 ±3.9	77.0 ±1.8	7.2 ±4.3	10.3 ±6.2
Quinby Inlet	Parramore-Hog	-6.9 ±2.6	-0.3 ±2.4	-6.6 ±1.0	89.1 ±3.6	98.0 ±1.5	8.9 ±3.9	10.0 ±4.4
Great Machipongo Inlet	Hog-Cobb	-10.0 ±4.7	-1.5 ±4.1	-8.6 ±1.9	215.3 ±5.6	220.5 ±2.4	5.3 ±6.1	2.5 ±2.8
Sand Shoal Inlet	Cobb-Wreck	-18.1 ±3.4	-2.9 ±3.0	-15.2 ±1.4	126.9 ±4.2	141.1 ±1.8	14.2 ±4.6	11.2 ±3.6
New / Wine / Little/ Ship Shoal/ and Smith Island inlets (combined)	Wreck-Fishermans	-10.0 ±2.6	-15.3 ±2.0	5.4 ±1.2	141.4 ±3.1	120.7 ±1.1	20.7 ±3.2	14.6 ±2.3
VES Wide Total (sum of all inlets)		-62.9 ±22.4	-36.3 ±3.4	-26.6 ±20.5	696.2 ±25.4	695.9 ±10.6	-0.3 ±27.6	0.0 ±4.0

Figure DR1. A) Baysheds of the Virginia barrier islands. Values in parentheses are change in tidal prism (1870–2009; negative values represent decrease; data from Table DR5). Note large decreases in northern rollover-dominated islands and increases associated with backbarrier marsh loss in southern islands. Satellite image is modified from NASA Blue Marble i-cubed 15m eSAT imagery. B) overview and C)-E) zoom-in maps of marsh gain/loss associated with bay expansion, upland migration, and landward migration of Assawoman through Smith islands between mid/late-1800s and 2009. Dashed square in (B) shows region highlighted in Figure 1b-d.



2.3. Comparisons of Marsh Area Change with Results of Earlier Works

Our work presents the longest (*ca.* 140 years) synthesis of marsh-area change along the VBI, and the first to quantifiably relate these changes to tidal prism, especially at the system scale. A number of previous studies have sought to quantify changes in marsh and open-water area over shorter time periods (maximum 100 years; Knowlton, 1971) and within select sub-sections of the VBI (Knowlton, 1971; Kastler and Wiberg, 1996; Erwin et al., 2004; Sepanik and McBride, 2015) (Table DR6).

For example, Sepanik and McBride (2015) studied marsh change within the Wachapreague Inlet bayshed (southern Cedar Island and northern Parramore Island; Figure DR1) at two different time periods (1957–1994 and 1994–2012). They found that barrier migration played an outsized role in marsh loss, accounting for 45% of loss between 1957 and 2012. Moreover, whereas burial and exposure were responsible for the large majority of loss within the section of the bayshed fronted by the Cedar Island, overwash played almost no role in marsh loss within the section of the bayshed fronted by Parramore Island, which has historically been stable to erosional along its northern end. Marsh loss in this southern half of the bayshed was caused primarily by wind-driven waves and tidal currents.

We find that that our 2009 TP* value for the bayshed of Wachapreague Inlet (Figure DR1a) (75–79 x 10^6 m^3) is similar to the tidal prism calculated by Richardson et al. (2015) for 2010 (50–65 x 10^6 m^3). Furthermore, we find that TP* increased by 10.5% between 1870 and 2009 (Table DR5), a value that also compares favorably to earlier studies of the change in Wachapreague Inlet tidal prism (+6.6% for 1871–2013; +5.8% for 2007–2013; Fenster et al., 2011; Richardson et al., 2015). Differences in our results and those of earlier studies are largely methodological: we apply a simple formula based on marsh and open-water area at both time periods to calculate changes in a *proxy for tidal prism*, whereas Fenster et al. (2011), Richardson (2012) and Richardson et al. (2015) rely on inlet cross-sectional-area / tidal-prism relationships for earlier time periods and direct measurement of water flow through the inlet for recent periods to calculate tidal prism volumes.

Similarities extend to marsh area changes: we observe the same spatial diversity in responsible mechanisms for marsh loss as Sepanik and McBride (2015) between the northern and southern halves of the Wachapreague Inlet bayshed (Table DR6; Figure 1d). We also find nearly equal losses in marsh from 1870 to 2009 due both to barrier island migration (3.2 km^2;

49%) and backbarrier processes (3.3 km^2; 51%), also with a small predominance of the latter. By contrast, our calculated overall marsh-loss rate of 0.08 % yr^{-1} (0.05 km^2 yr^{-1}) for the period 1870–2009 is only 1/3 of those calculated for the more recent 55-year period, indicating an average increase of more than an order of magnitude during the latter 20th and early 21st centuries as compared with the late 1800s and early 1900s. However, this value is likely partially inflated. Even assuming no methodological differences and 100 % overlap in spatial coverage, the record of McBride and Sepanik (2015) starts 87 years after ours. Given that marsh loss has been an ongoing process in the Virginia barrier islands since at least the 19th century, Sepanik and McBride (2015) will have a smaller starting marsh area, and their loss rates as a percent of that area will appear higher than ours.

Yet, it is also probable that much of the observed acceleration in marsh loss is real. Sepanik and McBride (2015) observed a 160% increase in marsh loss rates for this same area between 1957–1994 and 1994–2012. Likewise, Erwin et al. (2004) found that interior marsh retreat at Curlew Bay, located within Wachapreague Inlet bayshed, increased 3.5x due to edge erosion during a similar time period (1949–1967 and 1967–1994) (Table DR6). However, given the overwhelming role of burial and exposure in marsh loss along Cedar Island, this increase can also be attributed to a recent acceleration in shoreline retreat (see section 2.2). Indeed, Sepanik and McBride (2015) documented a nearly 3x increase in barrier-driven marsh loss in the Wachapreague Inlet bayshed between 1957–1994 and 1994–2012 records (Table DR6). Extrapolating these findings into the late 19th and early 20th centuries, Gaunt (1991) surmised that Cedar Island transitioned from erosional to migrational in the early 1960s. Hence, it is reasonable that acceleration in marsh loss can be attributed to the onset of wide-scale overwash and front-side exposure of marsh in the northern half if the Wachapreague Inlet bayshed.

Table DR6. Comparison of rates of change of marsh and open-water area from this study and earlier works.

			Total marsh change			**Barrier-driven change**			**Non-barrier-driven change**		
Spatial Coverage	**Source**	**Years studied**	**Marsh area change km^2**	**Area change rate $km^2\ yr^{-1}$**	**Annual percent loss % yr^{-1}**	**Marsh area change km^2**	**Area change rate $km^2\ yr^{-1}$**	**Annual percent loss % yr^{-1}**	**Marsh area change km^2**	**Area change rate $km^2\ yr^{-1}$**	**Annual percent loss % yr^{-1}**
Wallops to Fisherman's islands	Knowlton, 1971	1852/71–1962	-50.7	-0.507	-0.16 %	-33.0	-0.33	N/A	-17.7	-0.18	N/A
Chimney Pole Marsh (behind Hog Island)	Kastler and Wiberg, 1996	1949– 1990	N/A	N/A	N/A	N/A	N/A	N/A	-0.8	-0.020	-0.26 %
Southern Parramore Island Marsh	Kastler and Wiberg, 1996	1982– 1990	N/A	N/A	N/A	-0.04	-0.005	-0.90 %		N/A	N/A
Curlew Bay (within Wachapreague Inlet Bayshed)	Erwin et al., 2004	1949– 1967	N/A	N/A	N/A	N/A	N/A	N/A	-0.1	-0.004	-0.09 %
		1967– 1994	N/A	N/A	N/A	N/A	N/A	N/A	-0.4	-0.014	-0.32 %
		1949– 1994	N/A	N/A	N/A	N/A	N/A	N/A	-0.5	-0.011	-0.23 %
Gull Marsh (behind Cobb Island)	Erwin et al., 2004	1967– 1975	N/A	N/A	N/A	N/A	N/A	N/A	-0.3	-0.032	-0.79 %
		1975– 1994	N/A	N/A	N/A	N/A	N/A	N/A	-0.4	-0.023	-0.59 %
		1967– 1994	N/A	N/A	N/A	N/A	N/A	N/A	-0.7	-0.026	-0.65 %
Mockhorn Island (behind southern VBI)	Erwin et al., 2004	1949– 1967	N/A	N/A	N/A	N/A	N/A	N/A	1.0	0.057	0.19 %
		1967– 1994	N/A	N/A	N/A	N/A	N/A	N/A	1.9	0.070	0.02 %
		1949– 1994	N/A	N/A	N/A	N/A	N/A	N/A	1.2	0.026	0.09 %
Wachapreague Inlet Bayshed (southern Cedar, northern Parramore)	Sepanik and McBride, 2015	1957– 2012	-5.9	-0.107	-0.24 %	-2.6	-0.048	-0.55 %	-3.2	-0.059	-0.17 %
		1957– 1994	-3.4	-0.093	-0.20 %	-1.2	-0.033	-0.35 %	-2.2	-0.059	-0.17 %
		1994– 2012	-2.4	-0.136	-0.32 %	-1.4	-0.077	-0.95 %	-1.1	-0.059	-0.17 %
Wachapreague Inlet Bayshed	This study	1870– 2009	-6.5	-0.047	-0.09 %	-3.2	-0.023	-0.04 %	-3.3	-0.024	-0.04 %
Assawoman to Smith islands (combined system)	This study	1870– 2009	-62.8	-0.452	-0.14 %	-32.2	-0.232	-0.07 %	-30.6	-0.220	-0.06 %

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