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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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ABSTRACT

Coupling between barrier islands and their associated backbarrier environments (salt marsh, tidal flats) leads to complex ecogeomorphic feedbacks that are proposed to control the response of barrier island systems to relative sea-level rise. This study tests the applicability of these still theoretical concepts through investigation of the Virginia barrier islands, which are located in a hotspot of accelerated sea-level rise. Using historical maps and photographs from 1851 to 2010, we determine that rapid landward island migration (1–6 m yr^{-1}) is leading to backbarrier area reduction and large-scale salt marsh loss (63 km^2 or 19%) at a rate of 0.45 km^2 yr^{-1}. Landward barrier-island migration far outpaces upland marsh migration and was responsible for 51% of marsh loss, with the remainder due to backbarrier processes (*e.g.,* edge erosion). In direct contrast to proposed ecogeomorphic feedbacks linking barrier island and backbarrier environments, shoreline

retreat rates were not related to changes in backbarrier marsh, open-water areas, or tidal prism. Rather, these results indicate that, for barrier island systems already undergoing migration, the primary barrier-backbarrier coupling is the loss of marsh and tidal-flat area because of barrier-island migration itself.

INTRODUCTION

Barrier islands are shore-parallel, elongated sand bodies that front 10% of the world's coastlines (Stutz and Pilkey, 2011) and are backed by backbarrier marshes, tidal flats, and lagoons, all of which serve to buffer coastal environments and human development against relative sea-level rise (RSLR) and storms. Barrier islands and their associated backbarrier environments (here called "barrier systems") support diverse faunal communities and provide a wide range of ecosystem services and (Barbier et al., 2011). Over historical time, *ca.* 70% of the world's barrier island shorelines – and 68% of those along the U.S. New England and Mid-Atlantic coasts – are eroding (Bird, 1985; Hapke et al., 2013). These changes primarily reflect forcings by RSLR, which shifts the coastal areas affected by erosive forces (*i.e.*, waves and inundation) landward (Vellinga and Leatherman, 1989), and changes in available sediment quality and quantity (Stutz and Pilkey, 2011). At the same time, backbarrier salt marshes, which appear to have high resilience to RSLR (Kirwan et al., 2016), are threatened by other anthropogenic stressors, including eutrophication and sediment supply reduction (Kirwan and Megonigal, 2013).

Historically, marsh and barrier island evolution have been treated separately, but recent work suggests that important couplings exist between their respective processes. Modeling by Brenner et al. (2015) and Lorenzo-Trueba and Mariotti (2015) indicates that backbarrier width and substrate are both important determinants in island migration and

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response to RSLR, where islands with a sandier substrate and wider backbarrier environment migrate landward more slowly. Similar work by Walters et al. (2014) and Rodriguez et al. (2013) emphasize that overwash and aeolian processes are an important sediment source for backbarrier marshes, allowing them to survive higher RSLR rates than isolated marshes, and that the presence of island-adjacent backbarrier marshes slows landward barrier island migration rates. Such ecogeomorphic feedbacks indicate that these systems must be analyzed holistically to predict the response of barrier systems to global change.

Barrier-backbarrier couplings have also been predicted to drive the rapid degradation of barrier systems as a result of accelerated RSLR via “runaway transgression” (FitzGerald et al., 2008). This conceptual model predicts that under rapid RSLR rates, the backbarrier environment of mixed-energy barrier systems will undergo submergence, converting marsh to open water and leading to an increase in tidal prism (the volume of water transferred between the backbarrier and coastal ocean during a half tidal cycle) and an attendant increase in the size of sandy ebb-tidal deltas. This process would sequester sand otherwise available to adjacent islands, causing erosion-driven narrowing to accelerate. Eventually, these processes would lead to island breaching and rapid landward migration, destroying ecosystems and forfeiting the mainland protection and storm resistance provided by barrier systems.

Linking the evolution of barrier island and backbarrier environments through complex ecogeomorphic feedbacks represents an innovative framework for assessing the stability of coastal barrier systems, yet remains largely untested with field observation. Here, we test whether these concepts indeed govern the integrated evolution of barrier systems by analyzing the 150-year geographic evolution of nine largely undeveloped, mixed-energy barrier systems along the Eastern Shore of Virginia (the Virginia barrier islands; VBI).

STUDY AREA

The southern 100 km of the U.S. Delmarva Peninsula is bounded on its eastern side by a chain of largely undeveloped mixed-energy barrier islands. Our study area included the nine barrier systems from Assawoman to Smith islands (Fig. 1). These islands are 3–12 km long, 100–1000 m wide, are located 2.0–13.5 km offshore, and are backed by varying proportions of salt marshes, tidal flats, and shallow (1–2 m) open-water bays. The VBI are sub-divided into three geomorphic groups (Fig. 1): (1) a northern group characterized by parallel retreat (landward migration); (2) a central rotational group characterized by classic drumstick morphology; and (3) a southern group undergoing non-parallel beach retreat (Leatherman et al., 1982; Rice and Leatherman, 1983). Tropical and extratropical storms and their associated wave regimes drive a net southerly longshore transport along the ocean side of this system.

The VBI have experienced some of the highest rates of RSLR along the US Atlantic Coast: at Kiptopeke, VA (see location, Fig. 1) rates over the past 50 years were *ca.* 3.7 mm yr^{-1} (Boon and Mitchell, 2015. The VBI are allowed to erode and migrate without human interference, making them the largest natural barrier system along the U.S. Atlantic Coast, and an excellent location to test how barrier islands respond to accelerated RSLR in the absence of development.

METHODS

Historical shoreline positions (mean high water) along the VBI were digitized for 1851–1997 by Himmelstoss et al. (2010). We delineated an additional set of shoreline positions from 2010 LiDAR (USGS, 2011) following procedures of Himmelstoss et al. (2010). We then calculated shoreline change rates for this combined dataset along transects spaced at 50 m intervals as the slope of linear regressions between shoreline date and position using the Digital Shoreline Analysis System (DSAS) plugin for ESRI ArcGIS (Thieler et al., 2009). We computed both long-term (1851/2–2010) and short-term (1851/2–1910/1; 1980–2010) island-averaged rates. Errors in shoreline-change rates were determined after Hapke et al. (2011); see data repository for details.

Historical backbarrier marsh and water areas were derived from NOS T-sheets (Table DR1) by digitizing the marsh-water boundary at map scale (1:20,000). Classification of 2009 aerial imagery of the VBI (VGIN, 2009) using unsupervised classification in ArcGIS was manually down-sampled to the 1:20,000 resolution of historical maps, thereby excluding narrow interior marsh creeks, as in the T-sheets. Because the T-sheets were mapped at different years (Table DR1), we normalized all historical marsh areas to the mean map year (1870) by assuming marsh area changed at a constant rate from the mapping year to 2009.

The VBI were sub-divided into individual island systems based on hydrodynamic properties. “Baysheds” — the areas drained and filled by a given inlet during ebbing and flooding tides — were delineated using bathymetry and topography, creating a marine equivalent of watersheds. Each island is hydrologically associated with the two baysheds (Figure DR1a), corresponding to its two adjacent inlets; thus, the “barriershed” and its associated tidal prism for a given island is herein defined as the sum of those two associated baysheds. TP* (a proxy for tidal prism based on local tidal range [1.4 m] and relative area of backbarrier open-water and intertidal land; detailed calculation in Data Repository), marsh extent, and changes therein were calculated for each barriershed and compared to shoreline change rates.

RESULTS

Long-term (1850/1–2010) island-averaged shoreline-retreat rates are 1.2–6.2 m yr^{-1}; the average system-wide retreat rate was 5.1 m yr^{-1} (Table DR2; Fig. 1), consistent with system-wide 20th century estimates of *ca.* 5 m yr^{-1} (Leatherman et al., 1982). Short-term (1980–2010) retreat rates were generally higher, reaching nearly 20 m yr^{-1}. System-wide short-term shoreline retreat was 7.0 m yr^{-1}, which is more than 25x higher than the average retreat rate for the Mid-Atlantic and New England coasts (Hapke et al., 2013). Previous studies (e.g., Richardson and McBride, 2007, 2011; Nebel et al., 2012) have documented similar shoreline change rates for individual VBI, including the observed recent acceleration (see data repository and Table DR3 for complete discussion).

Modern barriershed TP* values range from 35×10^6 m^3 to 362×10^6 m^3 (Table DR4, DR5). Net change in TP* (1870–2009) ranges from a loss of 16.6×10^6 m^3 (−19.5%) to a gain of 19.5×10^6 m^3 (+4.4%) (Fig. 2). Total change in TP* within the study area was a loss of < 0.1% ± 4%. Individual baysheds experienced changes in TP* ranging from +11% where backbarrier marsh loss was greatest, to −31% in regions experiencing a decrease in backbarrier area due to island rollover (Figure DR1). Changes in marsh area were calculated as a net loss between 1870 and 2009 of 62.9 km^2, or 19.3% of the 1870 marsh extent, a rate of 0.45 km^2 yr^{-1} (0.1% yr^{-1}). This is lower than more recent rates observed in subsections of the VBI (Sepanik and McBride, 2015 and

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references therein), likely reflecting a late 20th century acceleration in marsh loss (see data repository and Table DR6 for complete discussion). As first recognized for the VBI by Knowlton (1971), we observe that burial resulting from island migration (calculated as the area of historical marsh located seaward of the 2009 island-backbarrier shoreline) is responsible for the majority (32.3 km^2; 51.4%) of marsh loss across the VBI (Figs. 2a, DR1; Table DR4). Although our methods cannot capture conversion of high marsh to low marsh, we find no evidence of interior marsh drowning. Backbarrier marsh loss (30.6 km^2) is largely along the edges of open-water bays (Fig. 1d): such locations have larger fetch, thereby allowing for the development of larger waves and enhanced marsh-edge erosion (Mariotti and Fagherazzi, 2013; McLoughlin et al., 2015).

DISCUSSION

Barrier island / backbarrier ecogeomorphic couplings have been proposed as a dominant driver of barrier system change in response to RSLR. For example, exploratory numerical models of landscape-scale ecomorphodynamic couplings (e.g., Lorenzo-Trueba and Ashton, 2014; Walters et al., 2014; Brenner et al., 2015) point to mutually beneficial coupling between marshes and barrier islands. Similarly, the conceptual "runaway transgression" model (FitzGerald et al., 2008) predicts that submergence of backbarrier marshes under conditions of rapid RSLR will lead to an increase in backbarrier open-water area and tidal prism, causing an increase in the number and size of tidal inlets, sand sequestration in ebb-tidal deltas, and attendant accelerated beach erosion and barrier island narrowing.

Our findings are in direct contrast to this conceptual framework: we find strong negative relationships between shoreline retreat rate and both modern TP* (2009) and

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change in TP* (1870–2009) in the VBI (Fig. 3), rather than the positive relationships anticipated from the runaway transgression model. This implies that islands fronting barriersheds with a larger and/or increasing tidal prism have historically had a slower retreat rate than those with a smaller and/or diminishing tidal prism. Shoreline retreat rates instead likely reflect drivers not directly related to barrier-marsh ecomorphodynamic feedbacks. For example, along the northern VBI, relatively high rates of island migration have been attributed to updrift sand trapping at Fishing Point, as Assateague Island progrades southward into deeper water (Leatherman et al., 1982); southerly extension of the resulting erosional 'Chincoteague Bight' may have caused the recent acceleration in shoreline retreat on Cedar and Parramore islands (Richardson and McBride, 2007; Oertel et al., 2008; Nebel et al., 2012). Other factors influencing variability in retreat rates may include geologic framework (Belknap and Kraft, 1985; Moore et al., 2010), differential subsidence rates (Leatherman et al., 1982), paleo-channels (Oertel et al., 2008), substrate and backbarrier sand/mud content and erodibility (Brenner et al., 2015), inlet ebb-delta dynamics influencing longshore transport (Fenster et al., 2016), and rates of storm-driven overwash (Lorenzo-Trueba and Ashton, 2014).

Regardless of the responsible mechanisms for shoreline change on any given island, we find that, especially given our observed minimal upland marsh migration (Fig. DR1), barrier island migration has driven a net loss of marsh and backbarrier area through time. Although a clear lack of evidence exists that this shoreline retreat is in direct response to changes in tidal prism at the scale of individual islands (Fig. 3), the near-zero net change (d of <0.1%) in TP* for the VBI as a whole between 1870 and 2009 (Fig. 2b) suggests that the VBI may be responding to coastal change in a system-wide (multi- inlet and island) manner. Unlike in the model of FitzGerald et al. (2008), which initiates with stable, non-migratory barrier islands that remain stationary as the marshes deteriorate and tidal prism increases, the VBI are sand-starved and have been eroding/migrating throughout the period of study. Thus, they may represent barrier systems already undergoing runaway transgression; in this case, the small net temporal change in TP* for the island chain as a whole may reflect a dynamic equilibrium in which gains in TP* due to backbarrier marsh loss across the system are balanced by losses in TP* due to rapid landward migration of the overwash-dominated northern and southern islands.

CONCLUSIONS

Along the VBI, we find that barrier-island retreat and the attendant narrowing of backbarrier regions is the primary ecomorphodynamic coupling between barrier islands and backbarrier environments. This coupling is also the leading driver of marsh loss in the mixed-energy VBI, accounting for over half of a net reduction in marsh area of 19% from 1870 to 2009. Such barrier-backbarrier interactions can be expected in similar mixed-energy barrier systems (e.g., South Carolina, New Jersey, Germany, and elsewhere), especially in cases where steep uplands prevent upland marsh migration from balancing losses to landward barrier island migration. Moreover, we find that this coupling is specific to those islands undergoing landward migration, and not simply shoreline erosion. Once narrowing leads to the initiation of island migration, it appears that this migration and associated marsh loss overwhelm the potential effects of interior marsh loss on barrier island stability. Artificial stabilization of barrier islands may provide short-term resistance to the impacts of migration; however, it decreases system resilience to RSLR in the long term (Rogers et al., 2015). Thus, regardless of the ability of vertical marsh accretion to keep pace with RSLR, large-scale marsh loss may be inevitable as barrier systems worldwide equilibrate to accelerated RSLR.

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327 FIGURES

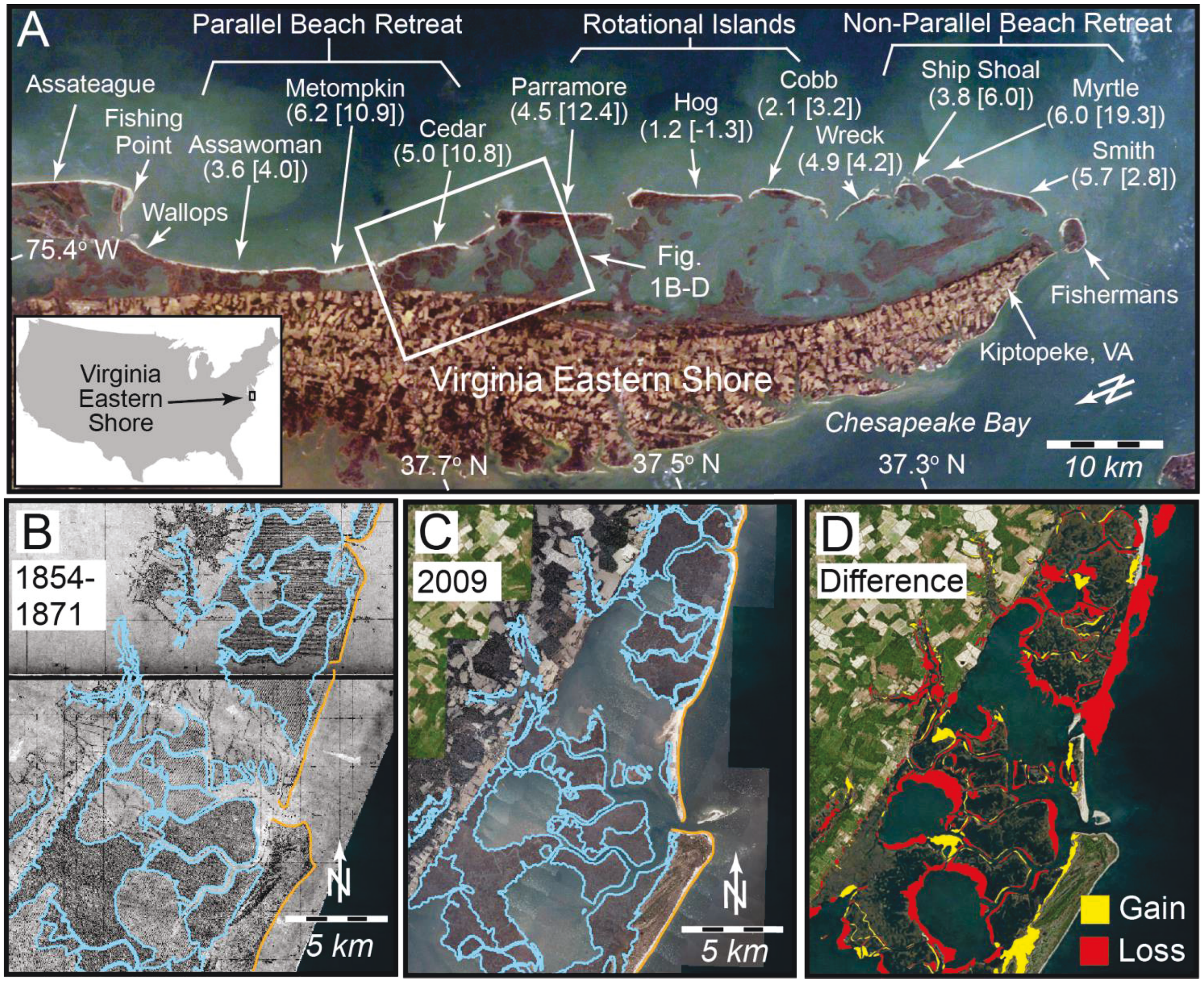

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Figure 1. A) Virginia barrier islands. Numbers in parentheses are island-averaged long-term (1851/2–2010) and short-term (1980–2010; in brackets) shoreline retreat rates in m yr^{-1} from linear regressions of shoreline position and date. Satellite image is modified from NASA image ISS006-E-13525. B)-D) Marsh extent (blue lines) behind Cedar and northern Parramore islands in the mid- to late-1800s (B) and 2009 (C), and the gain/loss in marsh area between in the intervening >140 years (D). 1854 (northern Cedar) and 1871 (southern Cedar and northern Parramore) data are derived from NOAA T-sheets T-01200 and T-00512, respectively. Modern data are derived from digital classification of 2009 aerial orthoimagery.

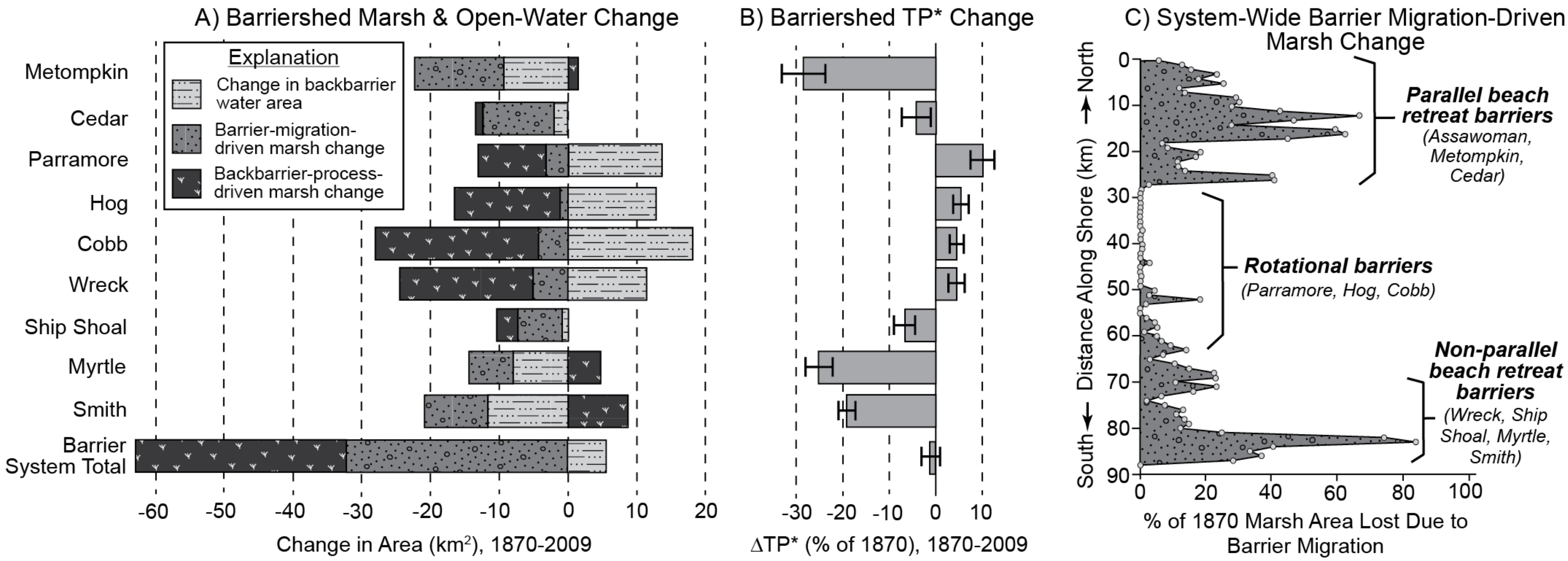

Figure 2. Marsh and tidal prism change along the Virginia barrier islands, 1870–2009. A) Change in open-water area and marsh area due to barrier migration and backbarrier processes (dominantly edge erosion). Barrier-migration-driven marsh loss is that marsh which has been buried by westward-migrating islands. B) Change in tidal prism (as denoted by TP*) along the Virginia barrier islands. C) Marsh loss (% of 1870) due to barrier migration within 1-km wide (alongshore) bins.

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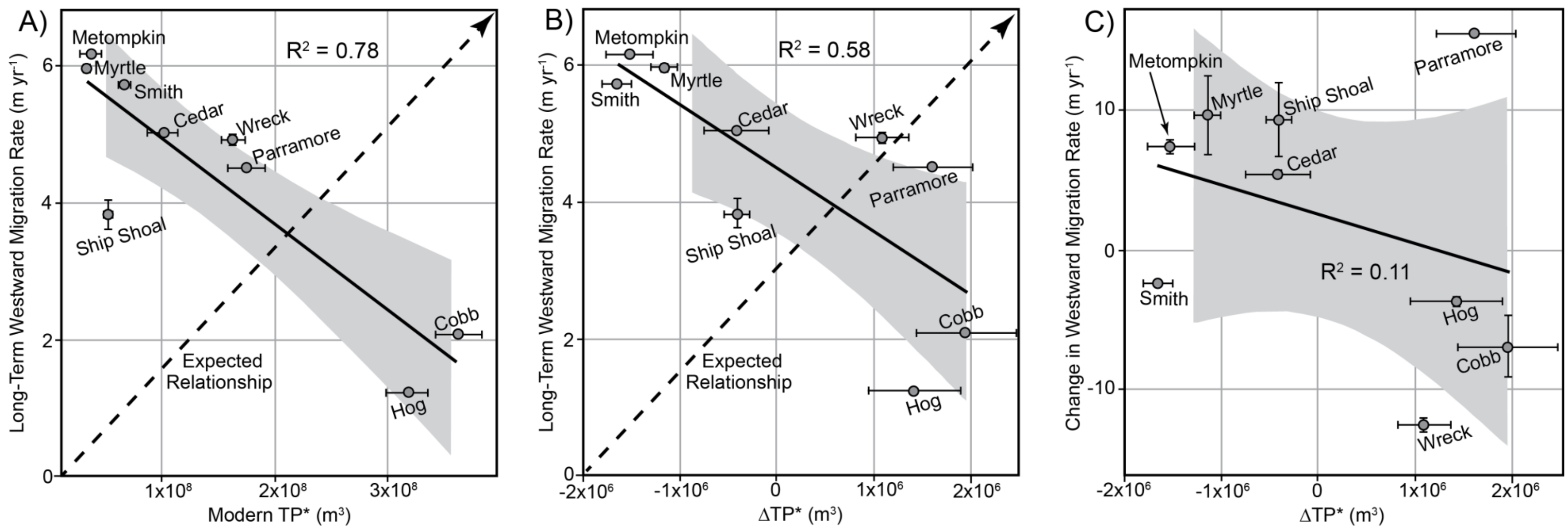

Figure 3. Comparisons between barrier retreat rates and backbarrier properties: A)-B) Long-term (1851/2–2010) retreat rates versus (A) modern TP* and (B) change in TP* (1870–2009). C) Change in retreat rate (difference between rate for 1851/2–1910/1 and 1980–2010) versus change in TP* (1870–2009). Solid lines: linear regression fits; Gray windows: standard error. Expected relationships are illustrated as a dashed line in each plot, with slope and intercept approximated for illustrative purposes. Errors are within data symbols where bars not shown.