# Marine transgression in modern times

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**Abstract** (150 words max)

Marine transgression associated with rising sea levels causes coastal erosion, landscape transitions, and displacement of human populations globally. This process takes two general forms. Along open-ocean coasts, *active* transgression occurs when sediment delivery rates are unable to keep pace with accommodation creation, leading to wave-driven erosion and/or landward translation of coastal landforms. It is highly visible, rapid, and limited to narrow portions of the coast. In contrast, *passive* transgression is subtler, slower, and impacts broader areas. It occurs along low-energy, inland marine margins, follows existing upland contours, and is characterized predominantly by the landward translation of coastal ecosystems. The nature and relative rates of transgression along these competing margins leads to expansion and/or contraction of the coastal zone, and—particularly under the influence of anthropogenic

interventions—will dictate future coastal ecosystem response to sea-level rise, and attendant, often iniquitous, impacts on human populations.

## 1. Introduction

Coastal-system response to sea-level rise is non-linear and non-uniform, and has been classically explained by the complex interplay between the rate of creation and infilling of accommodation (the space available below sea [or 'base'] level). When relative sea-level rise outpaces the influx of sediment, landward shoreline translation allows marine environments to invade formerly terrestrial ones, a process defined as 'marine transgression' (Curray 1964; Fischer 1961) (Figure 1). Yet, marine environments also invade terrestrial environments far from shorelines, in places above sea level, and with little to no sediment infilling (Tully et al. 2019; Kirwan & Gedan 2019). Thus, coastal-system response to sea-level rise may be described in terms of active transgression at the seaward margin of the coast (*i.e.*, the landward movement of shorelines and landforms) and passive transgression at the landward margin of the coast (*i.e.*, the landward or inland movement of ecosystems).

In the traditional view of active transgression, the resulting sedimentary sequences (Figure 2) commonly consist of terrestrial deposits overlain by coastal and then progressively deeper-water marine facies (a classic "fining-upward" sequence of depositional transgression) (Figure 2a). Along many modern continental shelves, however, the processes and resulting sedimentary sequences associated with marine transgression are far more complex. For example, where protected from open-ocean processes by fronting barrier-island systems, passive inundation along the interior transgressive margin allows wetlands (saltmarshes, mangroves, etc.) to migrate into former upland, terrestrial habitats (Kirwan et al. 2016; Figure 3a). Ecological transitions play a predominant role and shoreline translation patterns are complex, following local topography through inundation of low-lying areas. Not only may formerly upland depositional environments be persevered through drowning, but they are often replaced and buried by coastal ecosystems as this former wetland-upland margin is progressively overridden by backbarrier facies of varying sedimentary textures, and the sandy facies of the active, trailing-margin marine margin (Figure 2b). Continued transgression along the latter is planar, largely mainland-perpendicular, and results in removal of coastal deposits by wave action (Figure 3b), forming a transgressive ravinement overlain by shelf facies. Preservation of coastal systems is generally limited to thin lag deposits (Cattaneo & Steel 2003) or those emplaced deeper than the later ravinement, such as tidal-inlet fills (FitzGerald et al. 2012).

The dichotomy between these models of passive inundation and drowning of terrestrial environments and the dynamic competition between depositional and erosional processes along open-ocean coasts provides a framework for exploring modern marine transgression. With sea level already rising along most global coastlines—and >70 % of those projected to experience sea-level rise exceeding the global median of 20 cm with $2^{o}$ C of atmospheric warming (Jevrejeva et al. 2016)—marine transgression is widespread, affecting sandy, gravel, rocky, barrier, wetland, deltaic, and permafrost coasts globally. Here, we argue that marine transgression should be considered in terms of the marine energy supplied to the shoreline, and that multiple forms can co-exist in close proximity. For example, where waves, tides, and currents are sufficient to deliver, erode, or rework coastal sedimentary deposits and/or bedrock (along 'active' transgressive margins), transgression is predominantly a morphodynamic process, with its rate, and indeed even occurrence, dictated by net sedimentation associated with the balance among accommodation creation, in situ sediment production, and long- and cross-shore sediment transport. Although transgression in such dynamic systems (particularly those characterized by sandy beaches) has received the abundance of attention (*e.g.*, Mentaschi et al. 2018; Nicholls & Cazenave 2010; Vousdoukas et al. 2020), at least 30% of the coastal landscape will experience transgression through inundation and submergence (Lenz et al. 2016). This 'passive' transgression threatens low-lying, developed coastlines, built infrastructure and hardened landscapes (Hinkel et al. 2018; Vitousek et al. 2017), agricultural lands and forest ecosystems (Kirwan & Gedan 2019), and groundwater resources (Cantelon et al. 2022).

Despite their highly contrasting dynamics, shorelines experiencing active and passive transgression often can coexist within kilometers or less. Highly embayed estuarine coasts, for example, may experience wave-driven erosion along ocean-facing shores, but passive inundation along interior margins. Barrier-island systems are often characterized by two or more transgressive shorelines: the open-ocean beach undergoing erosion and/or migration, and the quiet-water upland margin where marshes, mangroves, or tidal flats onlap upon drowning uplands. Here, we review the processes influencing modern marine transgression along active and passive margins, and how the competition between active and passive transgression influences the spatial extent of the coastal zone. We conclude with implications for human populations living along these transgressing coasts, and a set of forward-looking research questions.

## 2. Active Transgression Along the Open-Ocean Coast

### *2.1. Active transgressive-margin processes*

The rate of sediment delivery to the coastal zone plays a preeminent role in shoreline change along active, open-ocean coasts, determining the rate of transgression, and indeed whether a coast is experiencing transgression at all. Controls on sediment supply are beyond the scope of this review, but can range from global tectonics and climate over geologic timescales to in-situ siliciclastic or biogenic sediment production, tidal-inlet dynamics, and shoreface erosion at the local and decadal scales. Examples of modern coastal progradation in spite of rising relative sea level (*i.e.*, 'normal' regression) are found globally. These commonly experience high sediment-input rates, and thus tend to be located at the mouths of rivers, zones of longshore wave convergence, depocenters of headland bypassing, or downdrift of eroding siliciclastic landforms (see review by Hein & Ashton [2020]). As a simple matter of contrast, open-ocean coastal systems experiencing a relative dearth of sediment as compared with the rate of accommodation creation are most likely to undergo transgression. Commonly, this is associated with coastal erosion: net loss of sediment from the active, subaerial coastal zone to reservoirs offshore or downdrift, leading to landward translation of the shoreline. However, transgression need not be net erosional. Beaches and barrier islands, for example, may simply migrate, retaining their sand volume and translating depositional environments landward. Moreover, a change in the rate of sea-level rise or sediment delivery is not a pre-requisite for initiation of transgression along active shorelines: "autoretreat"—a process largely limited to deltaic coasts—results from the progressive increase in the effective area of the subaqueous slope, whereby the constant input of sediment does not allow a steady accretion of the slope (Muto & Steel 1992).

Modern, active-margin transgression is commonly step-wise and interrupted by periods of seaward-building; that is, transgression is punctuated (Cattaneo & Steel 2003). For example, over short periods, a temporary transgressive episode (beach erosion) can be revered as beaches naturally "heal" seasonally or following storms, commonly through return of sediment temporarily stored on the shoreface (see reviews by Jackson & Short [2020] and Castelle &

Masselink [2023]). A similar case is that of beach rotation, in which transgression along part of a beach is matched by regression elsewhere through sediment redistribution within headland-bound beaches, typically alternating over timescales associated with individual storms, seasonal wave patterns, or longer-term changes in wave climate (Loureiro & Ferreira 2020). Over mesoscale (multi-decadal to centennial) periods, factors such as changes in wave climate (Kinsela et al. 2016; Vos et al. 2023) or net sediment input rates (Dean & Houston 2016) can lead to interruption of erosion / migration of coastal systems for decades or longer, irrespective of the rate of sea-level rise. One such example is the observed transitions of barrier islands between phases of erosion (transgression), migration (transgression), and growth (regression) (*e.g.*, Robbins et al. 2022). The open-ocean shorelines of such systems may be static or even prograde for years or decades, only to undergo rapid retreat associated with a single storm or the cumulative effect of sequenced storms (Fenster et al. 2022).

At the extreme, modern active-margin transgression can be a catastrophic process, in which the morphodynamic response of the active coastal system cannot keep pace with high rates of sea-level rise. Exhaustion of local sediment may lead to "extinction" of beaches (Luijendijk et al. 2018; Vousdoukas et al. 2020), or—in the case of barrier-island systems—rapid increases in accommodation may lead to overstepping, drowning, and/or rapid erosional retreat (Ciarletta et al. 2019), leading to partial preservation of former barrier deposits, such as those found on continental shelves globally (*e.g.*, Cooper et al. 2018; Emery et al. 2019; Manikam et al. 2022; Mellett & Plater 2018; Rampino & Sanders 1981). Importantly, Mariotti & Hein (2022) found that modern undeveloped barrier islands are primed for rapidly accelerating migration due to system inertia associated with built-up 'geomorphic capital' (*i.e.*, sediment reservoirs such as the shoreface, dunes, and barrier-adjacent tidal channels and deltas) within barrier systems. This pent-up transgressive response may be even greater in cases of anthropogenically stabilized shorelines where, if hardening removed and nourishment halted, available geomorphic capital may be quickly depleted as the island equilibrates to sea levels decimeters (or more) higher than when those islands could last freely migrate.

FitzGerald et al. (2008, 2018) present a case of transgression that is temporarily catastrophic, leading to large-scale punctuated transgression under only modestly higher rates of sea-level rise (Figure 4a). In this scenario, submergence and loss of broad marsh platforms behind mixed-energy barrier islands will lead to an enlargement of tidal prism and an attendant increase in the size of sandy ebb-tidal deltas (sequestering sand otherwise available to adjacent barriers). This process accelerates erosion-driven narrowing, breaching, and landward migration of those islands, thus leading to a period of "runaway" transgression until barriers re-establish closer to the mainland shoreline (the passive transgressive margin), with a much diminished backbarrier extent. Examples of large-scale, punctuated retreat and upslope re-establishment of active-margin coastal systems are also observed along deltaic, paraglacial, and permafrost coasts, generally associated with the exhaustion of local sediment supplies (Figures 4b–d).

### *2.2. Examples of active transgression across diverse coastal systems*

The morphodynamics of active-margin transgression reflect the geologic, sedimentologic, ecologic, and oceanographic setting of a given coastal system, and resulting rates of long-term landward shoreline movement can vary by several orders of magnitude (Table 1). Here, we briefly review the dynamics of transgression along a subset of such systems, to elucidate key commonalities and differences in factors responsible for the nature and rate of transgression globally. The rate of transgression in response to sea-level rise along any one of these coastal systems will be determined by a combination of allogenic oceanographic and climatic forcings, intrinsic sedimentologic and geologic factors, and human interference (Table 1).

*Mainland-attached beaches:* Beach and shoreface morphodynamics have been studied in great detail over many decades. Thorough recent reviews are dedicated to associated processes and factors controlling transgression over event to millennial timescales (*e.g.*, Gallop et al. 2020; Hamon-Kerivel et al. 2020; Jackson & Short 2020). Over long timer periods, where accommodation creation outpaces sediment supply, beaches respond to sea-level rise through either erosion and narrowing via sand loss to the nearshore and downdrift, or upslope profile translation without loss of beach width (Woodroffe 2002). Projections for future transgression are based on myriad cross-shore and planform engineering, morphodynamic, equilibrium-profile-based, and rules-based models, and include strongly disputed (Cooper et al. 2020) predictions of widespread, severe beach erosion in coming decades (Vousdoukas et al. 2020). Recent projections relying on more holistic approaches reveal that only narrow (< 50 m) mainland-attached beaches backed by seawalls are threatened by erosion-style transgression, whereas those free to migrate landward are unlikely to lose any width (McCarroll et al. 2021).

*Rocky coasts:* Transgression along coasts characterized by coastal cliffs, siliciclastic beaches within rocky headland-bound embayments, and coarse gravel and boulder beaches generally takes the form of landward erosion (Trenhaile 2016). Processes are slower than under equivalent forcings along sandy coastal systems (Table 1). Though driven by short-term, wave-driven processes (Earlie et al. 2017), transgression along rocky coasts responds predominantly to the rate of sea-level rise (Dickson et al. 2007), with studies predicting an acceleration in cliff erosion between twofold and an order of magnitude by 2100 under higher-end sea-level rise scenarios (Limber et al. 2018; Shadrick et al. 2022).

*Exposed permafrost coasts:* Coastal erosion along the 34% of the world's coasts comprised of permafrost (Lantuit et al. 2012) has been rapidly accelerating due to increases in the frequency, severity, and erosional efficiency of storms due to climate change and declining sea-ice extents (Jones et al. 2009). This process is associated with the release of long-buried soil carbon (Vonk et al. 2012) and can be further accelerated through interactions with warming-induced theromokarst formation in ice-bearing upland sediments (Ruz et al. 1992; Figure 4d). Along much of the Arctic Ocean, coastal erosion has nearly doubled within the last 60 years (Gibbs & Richmond 2015), and is projected to only accelerate further (by up to 0.8 m $yr^{-1}$ / °C increase in global mean surface air temperature) before the end of the century (Nielsen et al. 2022).

*Transgressive dune systems:* Although not shoreline-associated *sensu stricto*, large-scale transgressive dune systems and aeolian sand sheets are common along arid coasts and those with strong rainfall seasonality, where they can translate upon and bury upland, non-coastal facies at rates of 10s of meters per year (Hesp 2013). Future transgressive behavior is likely to be highly site specific, and strongly correlated with climate changes and human activities, but will undoubtedly lead to the burial and replacement of coastal and near-coastal upland environments with sand dunes characterized by variable degrees of mobility and vegetation densities (Hesp et al. 2022).

*Barrier-island systems:* Barrier islands respond to rising sea level through a combination of erosion (or 'encroachment': cross-shore island narrowing through loss of sand to offshore and/or downdrift reservoirs) and migration (or 'rollover': retrogradation of the full island system via overwash, island breaching, and aeolian transport) (Cowell et al. 1995). For the former, processes are largely aligned with those for mainland beaches. In contrast, barrier migration is influenced by myriad, complex, and often interwoven autogenic, geologic, morphodynamic, biophysical / ecogeomorphic, and anthropogenic factors (see recent reviews by McBride et al. [2022] and Moore & Murray [2018]), and can be associated with shoreface erosion of wetland "blue" carbon reservoirs (Theuerkauf & Rodriguez 2017) (Figure 3b). Field and model-based studies of barrier migration reveal a range of transgressive behaviors, including multiple forms of profile translation, stochastic processes and autogenic dynamics, and morphologic state changes (*e.g.*, between growth, narrowing, and migration) associated with punctuated transgression. For example, punctuated or discontinuous barrier retreat—in which long-term retrogradation is interrupted by periods of stasis or barrier growth—can be driven by dune dynamics (Reeves et al. 2021), autogenic feedbacks between shoreface slope, onshore-directed sediment fluxes, and overwash (Ciarletta et al. 2019), or exhaustion of erodible sediment reservoirs (Boyd et al. 1997; Forbes et al. 1995; Figure 4c).

*Deltaic coasts:* Deltas are among the most densely populated and threatened coastal systems (Syvitski and Saito, 2007). The majority of global deltas are likely to experience transgression in the near future, leading to a global loss of ~2% of delta area by 2100 (Nienhuis and Van der Wal, 2021). At a broad scale, transgressive processes will be morphologically complex, and inextricably linked to upstream river processes (see Neinhuis et al. [2023] for a recent comprehensive review). At a finer scale, deltaic coasts are commonly composed of an amalgamation of many different coastal landforms, including barrier islands, marshes and/or mangroves, permafrost, levees and crevasse splays, progradational beach, foredune-ridge, and chenier plains, and widespread shallow-water subaqueous shoals, among others. Along the active, outer margins of deltas, coastal transgressive behavior is expected to largely mimic that of the associated landforms. For example, Penland et al. (1988) present a model for the co-evolution of delta lobes and the barrier islands generated from associated sediments (Figure 4b).

## 3. Passive Transgression at the Low-Energy Upland Margin

### *3.1. Ecological transitions at the passive transgressive margin*

Inundation-style transgression occurs along low-energy estuaries and lagoons that can be located far inland from the open ocean coast. Unlike active transgression that results in conversion of land to water, passive transgression typically results in the replacement of one type of vegetated ecosystem with another. For example, sea-level rise has led to widespread migration of tidal marshes into upland forests (Kirwan & Chen 2022a), freshwater forested wetlands (White et al. 2021), and agricultural fields (Gedan et al. 2020) (Figure 5a, b). Although not the focus of this review, passive transgression also occurs as salt water intrusion converts freshwater marshes to mangroves (Chambers et al. 2015), and managed realignment converts agricultural land to salt marsh (Temmerman et al. 2015) (Figure 5c, d). These ecological transitions are often visually striking, marked by reduced crop yields, abandoned agricultural fields, and standing dead trees known as “ghost forests” (Kirwan & Gedan 2019; Tully et al. 2019) (Figure 3a).

Ecological transitions associated with passive transgression typically lead to vegetation types that are more flood and salt tolerant (Figure 5). In terrestrial forests, saltwater intrusion causes the expansion of shrubs and replacement of deciduous tree species with more salt-tolerant coniferous species and eventually herbaceous saltmarsh species (Anderson et al. 2022; Jobe & Gedan 2021; Langston et al. 2017). Immature life stages such as seedlings are more sensitive to flooding stress than mature trees, such that sea-level rise leads to a change in the structure of coastal forests even before marsh migration occurs (Kearney et al. 2019; Williams et al. 1999).

Finally, saltwater intrusion into lawns and farmland leads to unique plant assemblages, where abundant sunlight may favor native saltmarsh species (Anisfeld et al. 2017; Gedan & Fernández-Pascual 2019) over stands of invasive *Phragmites australis* that dominate retreating coastal forests (Smith 2013).

Passive transgression within coastal ecosystems also leads to physical and biogeochemical alterations to underlying soils. Progressive inundation of terrestrial forests leads to wetter, anoxic soils that accumulate organic matter and eventually receive mineral sediment from tides. Such a transition is characterized by an increase in porewater salinity, reduction in soil bulk density, and increase in soil organic matter content (Brinson et al. 1995). Responses are more complex where marshes migrate into freshwater forested wetlands. Generally, saltwater intrusion leads to increased ionic strength, alkalization, and sulfidation of soils (Tully et al. 2019). Although not universally observed (Noe et al. 2013), these changes would be expected to enhance decomposition of organic matter and in some cases lead to reduced accretion and peat collapse (Chambers et al. 2015; Charles et al. 2019; Noe et al. 2013), which could potentially increase inundation and accelerate an otherwise passive transgression (Miller et al. 2021).

### *3.2. Mechanisms and factors responsible for passive transitions*

Like active-transgression along high-energy coasts, sea-level rise is the dominant factor driving the inland migration of coastal ecosystems within passive-margin settings. However, unlike active-transgression, clastic sedimentation plays little to no role in passive-transgression, which is instead predominantly influenced by upland slope. For example, observations of ghost forests are extensive along the U.S. mid-Atlantic coast, where rapid relative sea-level rise has inundated large land areas characterized by a gently sloping, coastal plain topography (Kirwan &

Gedan 2019; McDowell et al. 2022). Rates of marsh migration into coastal forests along the U.S. Atlantic Coast began accelerating in the late 19th Century, coincident with an acceleration in eustatic sea-level rise, and have increased roughly synchronously across sites in each succeeding decade (Schieder & Kirwan 2019). Similarly, tidal freshwater forests were largely stable through the Holocene but have transitioned towards marshes in recent decades to centuries (Jones et al. 2017), and rates of saline mangrove migration into freshwater marshes have increased during the last century (Gaiser et al., 2006) (Supplementary Table 1). Like transgression along open-ocean coasts, gradual accommodation-driven forest retreat is punctuated by storm events and other disturbances that lead to abrupt forest mortality and rapid transgression (Fagherazzi et al. 2019; Miller et al. 2021; Ury et al. 2021). Unlike sandy, active-transgression coasts—which can return to pre-storm conditions through natural return or replacement of eroded sand—these ecological transitions are largely nonreversible. However, similar to siliciclastic coasts, forest biomass and forest retreat rates over longer time periods are correlated with rates of sea-level rise and the elevation and slope of adjacent uplands (Chen & Kirwan 2022a; Flester & Blum 2020; Schieder & Kirwan 2019), suggesting sea-level rise as the dominant driver of passive, inland transgression.

Mechanistically, increased inundation and salinity of coastal forests leads to tree mortality through the interactive effects of osmotic stress and carbon starvation (McDowell et al. 2022). Salt accumulation in forest soils leads to reduced sap flow (Krauss & Duberstein 2010) and a shorter growing season (Brinson et al. 1985; Chen & Kirwan 2022b), such that respiration demands exceed photosynthetic supply and trees cannot maintain growth (McDowell et al. 2022). At the same time, marsh plants adapted to wet, saline soils migrate landward beneath a thinning forest canopy (Langston et al. 2017; Smith & Kirwan 2021), often led by the invasive reed, *Phragmites australis* (Jobe & Gedan, 2021; Smith 2013). Predictions of marsh migration into adjacent uplands are based on assumptions of passive inundation of a static topography (Buchanan et al., 2022; Molino et al. 2021; Osland et al. 2022), but newly emerging concepts connecting ecohydrology and root-zone processes likely mediate ecosystem transgression (Guimond & Michael 2021; Messerschmidt et al. 2021; Nordio & Fagherazzi 2022). Nevertheless, vegetation change occurs more rapidly than shifts in underlying soils (Anisfeld et al. 2017), so that marsh migration and the transgression of coastal ecosystems may even precede the death of canopy trees.

## 4. The Role of Humans in Active and Passive Transgression

Humans are one of the world's great geomorphic agents, and can both directly and indirectly influence the rate and nature of transgression (Lazarus et al. 2016): even modest amounts of development can override natural processes, altering coastal system behavior across distances of hundreds of kilometers and for time periods lasting many decades (Armstrong & Lazarus 2019; Hapke et al. 2013). Along open-ocean coasts, direct human interference can accelerate transgression by reducing the resilience afforded by dunes (*e.g.*, Nordstrom 2000) or slowing beach recovery following storms (*e.g.*, Wernette et al. 2020); or slow transgression through hardening of eroding cliffs or permafrost (*e.g.*, Griggs & Patsch 2019; Liew et al. 2020), beach nourishment (*e.g.*, Lazarus et al. 2016), and emplacement of hard or soft engineering structures and/or 'living' shorelines (*e.g.*, Alves et al. 2020; Cooper & McKenna 2008a).

Along passively inundating transgressive margins, steep slopes, extensive dykes, seawalls, and polders can entirely prevent wetland migration into retreating uplands (Enwright et al. 2016; Gilman et al. 2008; Kirwan et al. 2016). Indeed, rates of lateral marsh migration are less than 0.1 m $yr^{-1}$ in the steeply sloping Elkhorn Slough Estuary (California, USA) (Wasson et al. 2013), and vary by more than an order of magnitude in different topographic settings even within the relatively gently sloping mid-Atlantic coastal plain (Flester & Blum 2020; Schieder et al. 2018) (Table 1). Globally, ghost forests have not been observed in highly developed coastal regions, such as Northwest Europe and Southeast Asia (McDowell et al. 2022; Kirwan & Gedan 2019). Even largely rural coastal regions such as the U.S. Gulf Coast and Chesapeake Bay include significant portions where transgression may be limited by impervious surfaces, anthropogenic barriers, and landowner desires to prevent migration (Field et al. 2017; van Dolah et al. 2020). Across the U.S., 90% of land expected to be inundated by a 1 m rise is sea level is privately owned (Titus et al. 2009). Landowner decisions to abandon or defend land are often manifested through the construction of ditches, agricultural tiling, and small earthen levees (Bhattachan et al. 2018; Hall et al. 2022) (Figure 5d). Nevertheless, the ability of these features to prevent migration is unclear (Hall et al. 2022), and preliminary work suggests that marsh migration into adjacent lawns and agricultural land operates in a manner that is grossly similar to natural, forested ecosystems (Anisfeld et al. 2017; Gedan & Fernández-Pascual 2019; Gedan et al. 2020).

## 5. Migrating Boundaries and the Changing Extent of the Coastal Zone

Sea-level rise is leading to a rapid reorganization of coastal ecosystems (Chen & Kirwan 2022a). Along coasts characterized experiencing both active (trailing-margin) and passive (leading-margin) transgression, these processes act in concert, altering the extent and nature of the coastal systems bounded by these margins (Figure 6). Active transgression typically leads to the loss of coastal ecosystems at their seaward margin, such as through burial and shoreface erosion of backbarrier salt marshes in response to island rollover (Deaton et al. 2017; Theuerkauf & Rodriguez 2017). Simultaneously, inundation along the passive transgressive margin leads to the expansion of coastal ecosystems, as saltwater intrusion propagates up freshwater tributaries (Ensign & Noe 2018) or into adjacent uplands (Kirwan et al. 2016) (Figure 5b). Therefore, the size of the coastal zone and the ecosystems that it contains can be conserved only if active transgression along trailing-margin, seaward margins is compensated by passive, leading-margin transgression further inland (Figure 6a).

Systems characterized by both rapid trailing-margin transgression and slow leading-margin transgression (*i.e.*, upland slopes that are steep or defended with anthropogenic barriers) are particularly sensitive to coastal-zone contraction (Figure 6b). This may occur in cases characterized by rapid barrier-island migration (Lorenzo-Trueba & Mariotti 2017) or where transgressive dune systems migrate into adjacent saltwater wetlands or lagoons, such as along the coast of southern Mozambique (Tinley 1987). In contrast, the coastal zone may increase in size where inundation along a gentle upland slope is paired with a slowly transgressing (or even regressing) open-ocean shoreline, such as those held in place either by a natural abundance of sediment or artificial stabilization (Figure 6c). Even just development upon barrier islands has been found to decrease storm overwash fluxes (Rogers et al. 2015), thus slowing trailing-margin transgression. Resulting backbarrier expansion can lead to destabilization and eventual deterioration and/or transgressive overstepping of the entire barrier system (Miselis & Lorenzo-Trueba 2017), a process documented in the recent geologic record (*e.g.*, Emery et al. 2019).

However, in reality, the net impact of transgression may be determined as much by the definition of coastal margins and the relative proportion of area influenced by active and passive transgression. For example, the largely undeveloped Virginia Atlantic Coast features barrier-island migration rates that are among the fastest in the world, driven by generally low sediment supply, rapid sea-level rise, and islands that are free to migrate in the absence of human development (Robbins et al. 2022). Here, landward island migration at ~4.5 m $yr^{-1}$ (Mariotti & Hein 2022) has exceeded marsh migration rates (0.04–0.45 m $yr^{-1}$; Flester & Blum 2020), resulting in a narrowing of the coastal zone through an approximate 7 % reduction backbarrier extent since the mid-1800s, and burial and/or shoreface erosion of ~32 $km^2$ of backbarrier marsh that was almost entirely uncompensated by migration into uplands (Deaton et al. 2017). However, the length of the barrier-fronted Delmarva Peninsula Atlantic coast subject to active transgression is small (~225 km) relative to the length of the many embayments and tributaries of the adjacent Chesapeake Bay subject to passive inundation (>18,000 km). Therefore, the net impact of active and passive transgression has been to increase marsh area by 48.4 $km^2$ (~2%) between 1984 and 2020 for the broader mid-Atlantic coastal region (Chen & Kirwan 2022a).

Anthropogenic barriers within the trailing and leading margins (Section 4) in modern, coupled active-passive transgressive systems fundamentally impacts coastal ecosystem size and functionality. Coastal New Jersey and North Carolina may be examples of systems where transgression leads to net backbarrier (marsh, lagoon) expansion, as barrier migration is slowed in part by human management (Pilkey et al. 1998; Riggs & Ames 2003) and wetlands migrate into an extensive, undeveloped coastal plain (Smith et al. 2013; Ury et al. 2021). In contrast, coasts and estuaries in Northwest Europe or the U.S. Pacific Coast are examples of systems where transgression leads to net marsh loss, because erosion at the seaward margin cannot be compensated by inland migration which is prevented by anthropogenic barriers (*i.e.*, “coastal squeeze”) (*e.g.*, Schuerch et al. 2018). Therefore, the specific location of anthropogenic influence within the transgressing coastal landscape potentially has a fundamental impact on the future evolution of coastal systems: stabilization of the seaward margin favors ecosystem expansion during transgression while stabilization of the landward margin favors ecosystem loss (Figure 6).

Despite local wetland losses associated with coastal squeeze in coupled active-passive systems, transgression at the global scale could potentially lead to a net increase in marsh area. Twenty-first century sea-level rise is predicted to lead to changes in saline wetland area that range from a 30% loss to a 60% grain, depending principally on the likelihood of coastal flood defense for growing coastal populations (Schuerch et al. 2018). Historically, processes that create wetlands (restoration, delta growth, and migration) have roughly balanced those that destroy wetlands (direct human alterations, erosion, inundation, barrier migration), leading to general conservation in marsh area globally over the last several decades (Murray et al. 2022). These observations suggest that wetland expansion along natural coasts could potentially compensate for transgression-induced contraction along developed coasts over large spatial scales (Schuerch et al. 2018; Molino et al. 2021). However, anthropogenic and topographic constraints to passive transgression lead to a highly heterogenous coastal response, where inland transgression occurs extensively in some locations but not at all in others (Brochert et al. 2018; Molino et al. 2021). Indeed, predictions of passive transgression suggest that compensation of marsh area may occur at large spatial scales (*e.g.*, Chesapeake Bay or Louisiana Gulf Coast), but that responses within individual watersheds could include either extensive marsh expansion or catastrophic marsh degradation (Brochert et al. 2018; Molino et al. 2021). These countervailing forces have important implications not only for ecosystem dynamics, but also for carbon cycling. Vegetated intertidal ecosystems sequester carbon in their soils at rates far surpassing terrestrial ecosystems (Mcleod et al. 2011), suggesting that passive transgression could increase soil carbon storage at the landward margin of the coastal landscape as carbon-rich wetlands replace terrestrial ecosystems (Wang et al. 2021). In contrast, active transgression at the seaward margin reduces the area of vegetated coastal ecosystems contributing to carbon sequestration, and at the same time releases carbon stored in soils into environments where its fate is unknown (*e.g.*, Theuerkauf & Rodriguez 2017). Preliminary numerical modeling at the global scale suggests that the combined impacts of active and passive transgression are to increase soil carbon accumulation rates in the coastal zone (Wang et al. 2021), but with important thresholds and a fundamental shift from carbon stored in the biomass of trees to carbon stored in wetland soils (Valentine et al., 2023).

## 6. Marine Transgression and Environmental Justice

### *6.1. Global inequities in the impacts of active and passive transgression*

Marine transgression—both active erosion and passive inundation—is already impacting human populations globally, with hundreds of millions more soon to be threatened (Kulp & Strauss 2019). Adaptation measures range from the individual to the collective, and include advancement (anthropogenic regression through, for example, land reclamation), defense (shoreline stabilization through beach nourishment, living shorelines, hardening structures, etc.), accommodation (improved design, planning, construction, and management), and retreat (*e.g.*, managed realignment, housing buybacks) (Williams et al. 2018; Mach & Siders 2021). Each approach comes with significant costs and benefits. For example, along the passive transgressive margin, those defense measures can help maintain the economic value of the adjacent upland (a local gain), but at the cost of the ecosystem services provided by the displaced wetlands (a global loss) (*e.g.*, Fagherazzi et al. 2019). Along open-ocean coasts, communities face significant political and financial pressures to maintain or expand existing protective structures or shoreline-stabilization strategies, thereby mitigating against adaptation and potentially increasing hazards (Fallon et al. 2017). Indeed, the global cost of defending the coast with dikes is far less than that of avoided flood damages (Hinkel et al. 2014). However, as the spatial scale or time window for considering coastal impacts of climate change and attendant public intervention grow, the case for public intervention becomes weaker, requiring the need to incorporate a social justice framework into management decisions (Cooper & McKenna 2008b). For example, inundation affects a large area of interior coast (including along the many necks, embayments, and tributaries of estuaries), much of which tends to be rural and home to socially vulnerable communities (Barbier 2015). It is also a relatively slow process as compared with active-margin transgression (Table 1), with impacts felt over lifetimes or generations. In contrast, processes such as storm flooding and beach erosion associated with active-margin transgression are fast, concentrated in a small area of the coast (near beaches), and—at least in much of the global north—predominantly impact relatively wealthy coastal communities with more political and social capital: characteristics that make these settings better targets for disaster relief funding (Lincke & Hinkel 2018).

Sea-level rise is likely to lead to widespread displacement of human populations, with the timing and nature of migration determined by myriad environmental, political, socioeconomic, and cultural factors (Hauer et al. 2020). Differences in both the physical vulnerability of the landscape—and of the social vulnerability of its inhabitants—to marine transgression highlight deep disparities in the societal impacts of transgression globally and regionally (Siders et al. 2019). Countries and population centers built upon deltas and small, low-lying islands and archipelagos are among the most immediately and disproportionally at risk from drowning and saltwater incursion associated with passive transgression, as well as land loss from along erosive active margins (Edmonds et al. 2020; Mycoo et al. 2022; Weir et al. 2017). Regions such as the Asia Indian Ocean, and East and Southeast Asia are particularly at risk for population displacement (Nicholls et al. 2011), affecting, for example, up to 2.1 million people in Bangladesh by 2100 (Davis et al. 2018).

At a much finer scale, discriminatory historical policies and practices such as redlining—the now-illegal practice in the U.S. of denying loans or restricting services based on the racial characteristics of a neighborhood—forced communities of color and those with less social capital into predominantly flood-prone areas of major cities, leaving them particularly vulnerable to the effects of ongoing transgression (*e.g.*, Herreros-Cantis et al. 2020). Outside of major urban areas, these same disparities often exist along socioeconomic lines. For example, along the low-gradient coasts of Chesapeake Bay, inland marsh migration is often to the detriment of rural coastal communities, destroying agricultural lands, flooding everything from transportation infrastructure to cemeteries, and displacing residents (van Dolah et al. 2020). Elsewhere, a combination of small population size, non-vital or deteriorating infrastructure, and extreme threats from transgression may leave relocation as the only economically and socially feasible response. Decisions to raise homes or build levees based on cost-benefit logic promote disproportionate retreat in low-income or minority communities (Siders 2019). These conditions are particularly salient for minoritized or otherwise socially vulnerable populations, such as Alaska Native communities located along the eroding Arctic coast (Bronen & Chapin 2013) or the American Indian community of Isle de Jean Charles, which is currently being relocated within the Mississippi River Delta (Simms et al. 2021). Decisions surrounding such actions, or indeed the broader range of coastal adaptation strategies in the face of marine transgression, are inherently fought and, as noted by Barra (2021), a "geophysical and social process upon which racial inequality is forged and contested."

### *6.2. A case study of the human impacts of dual-shoreline transgression*

Here, we present a case study of the interplay of active and passive transgression, and the implications for physically and socially vulnerable coastal communities, focusing on the present-day evolution of Tangier Island (Virginia, USA), home to an isolated community within Chesapeake Bay recognized for its rich cultural history. The population of Tangier has declined from ~1000 to ~400 residents in the last 120 years, driven by a combination of socioeconomic factors and transgression-driven reductions in upland area (Wu & Schulte 2021). Scientific, media, and policy-based discussions have largely focused on mitigating active transgression (*i.e.*, coastal erosion) (Swift 2018). Shoreline erosion has consumed roughly 2/3 of the island area since 1850 (Schulte et al. 2015). A rock revetment was constructed in 1990 to stabilize the island's exposed western shore, where erosion (3.6–4.8 m $yr^{-1}$) historically was most rapid (Mills et al. 2005) (Figure 7); and the community continues to request revetments to stabilize other portions of the island (Schulte et al. 2015; Wu & Schulte 2021).

However, passive transgression on Tangier remains largely unaddressed. The inhabited portions of the island are located along narrow ridges at elevations of 1.0–1.5 m above mean sea level (Mills et al. 2005). In these areas, passive transgression has reduced upland area from 32.8 to 12.5 ha (1967–2019) (Wu & Schulte 2021). Indeed, the northern portion of Tangier Island ("Uppards"; Figure 7) has converted entirely to marsh and was last inhabited in 1928 (Swift, 2018). While the rock revetment has stabilized the eroding western shoreline (Mills et al. 2005), passive transgression is predicted to convert remaining uplands to wetlands by 2051 (Wu &

Schulte 2021). Mitigation strategies for passive transgression (*e.g.*, small dykes and ditch networks) have not been proposed on Tangier, and benefits have been inconclusive elsewhere in the region (Hall et al. 2022). Thus, the fate of small island communities, such as Tangier, depend on the management of both highly visible active transgression (conversion of land to water) and less visible passive transgression (conversion of upland to wetland); with decisions surrounding defense, accommodation, or retreat driven not only by the physical realities of the systems, but the social, political, and economic capital of their peoples.

**7. Future Issues**

1. What role do nonlinearities and time lags in coastal-system response to sea-level rise play in leading to unanticipated complexities associated with future marine transgression?
2. Will transgression result in the global maintenance, expansion, or contraction of the coastal landscape, and how will the ecosystem and human responses vary regionally?
3. How will transgression influence the function of the coastal zone? Will shifting coastal ecosystems simply result in the shifting of ecosystem services (*i.e.*, habitat, primary productivity, flood protection, carbon sequestration, and nutrient cycling) or does the age and location of ecosystems matter?
4. How will an emerging understanding of ecogeomorphic and socio-ecological couplings improve predictions along co-evolving active (trailing) and passive (leading) transgressive margins?
5. What unseen intersectionalities between socioeconomic and environmental factors drive human risk and response to marine transgression?

6. To what extent could passive transgression (salinization of freshwater ecosystems, and development of new marshes) help compensate for the effects of active transgression (erosion and submergence of barrier islands and associated marshes) on the strength of the coastal carbon sink?

## 7. Disclosure Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the objectivity of this review.

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## 10. Tables and Figures

***Table 1.*** Summary of rates and processes shaping modern marine transgression across active and passive transgressive margins. Source information for average rates is provided in Supplemental Table 1.

| Coastal System | Transgressive Process | Transgression Rate (avg. (range)) | Allogenic Factors Influencing Transgression | Intrinsic Factors Influencing Transgression | Anthropogenic Factors Influencing Transgression |
|---|---|---|---|---|---|
| **Active Transgressive Coasts** | | | | | |
| Mainland-Attached Beaches | Erosion or migration | 0.6 (-0.5 – 8.5) m $yr^{-1}$ | Wave climate; frequency, intensity, and sequencing of storms; longshore and cross-shore sediment availability and delivery rates | Upland slope; coastal orientation; bedrock-controlled planform accommodation; sediment texture; pre-storm beach and dune morphology; cementation of intertidal beach sediments | Beach nourishment; shoreline hardening; soft engineering structures |
| Rocky Coasts | Erosion | 0.1 (0.05 – 0.1) m $yr^{-1}$ | Wave climate; frequency, intensity, and sequencing of high-energy wave events | Bedrock / cliff lithology; shore platform profile; weathering rates; prevalence of bioerosion; autogenic sediment production rates; volume and texture of sediments on fronting beach (if any); ground-ice content (high-latitude coasts) | Cliff hardening |
| Permafrost Coasts | Erosion | 1.0 (0.0 – 5.5) m $yr^{-1}$ | Frequency and severity of storms; erosional efficiency of storms as associated with fetch, sea ice, sea level, and sea-surface and air temperatures | Ground near-surface temperature | Shoreline hardening |
| Transgressive Dunes and Sand Sheets | Erosion or migration | 7.0 (0.5 – 13.0) m $yr^{-1}$ | Wind and wave climate; precipitation amount and/or seasonality; frequency and intensity of storms, high-wind events, and fires | Availability and texture of sand in the upper shoreface and beach and erosional dune edge; vegetation cover; water table level | Alteration of vegetation cover through, planting / removal of vegetation, creation of artificial blowouts, and introduction of fertilizers, among others |

| | | | | | |
|---|---|---|---|---|---|
| Barrier Islands | Erosion or migration | 5.0 (-1 – 16) m $yr^{-1}$ | Wave climate; frequency, intensity, and sequencing of storms; longshore and cross-shore sediment availability and delivery rates | Framework / antecedent geology and topography; barrier lithosome sediment texture; biophysical / ecogeomorphic feedbacks arising from foredune dynamics and marsh-island couplings (*e.g.*, dune height and width; extent of backbarrier marsh); autogenic processes; inlet dynamics | Beach nourishment; shoreline hardening; soft engineering structures; overwash-inhibiting development |
| Deltaic Coasts | Erosion or migration (sub-system specific) | variable (3 – 38 m $yr^{-1}$) | Wave climate; frequency, intensity, and sequencing of storms; fluvial sediment delivery rates to the delta front; frequency of avulsion; migration of the location of river switching | Shallow delta lithosome sediment texture; biophysical / ecogeomorphic feedbacks; autogenic processes; inlet and distributary channel dynamics | Beach nourishment; shoreline hardening; soft engineering structures |
| **Passive Transgressive Coasts** | | | | | |
| Upland-Migrating Marsh | Inland migration | 20 (0 – 55) m $yr^{-1}$ | Frequency, intensity, and timing of storms; insect outbreaks; fire | Upland slope; estuarine salinity; root-zone subsidence; vegetation-groundwater feedbacks | Water management; dykes, ditches, levees, canals, & agriculture |
| Estuarine Elongation | Upstream migration | unquantified | Watershed freshwater discharge | River slope and upland slope; estuarine salinity; root-zone subsidence; vegetation-groundwater feedbacks | Water management; dams |
| Mangrove-Marsh Transitions | Inland migration | variable (0 – 61 m $yr^{-1}$) | Precipitation; freeze events; frequency, intensity, and timing of storms | Peat collapse; marsh accretion processes | Water management; dykes, ditches, levees, canals, agriculture, aquaculture |
| Adaptation & Managed Retreat | Inland and upstream migration | variable | Land use; populations; socio-economic variables | Upland slope; exposure to waves and currents | Flood-control structures; levees, dykes, agriculture, & aquaculture |

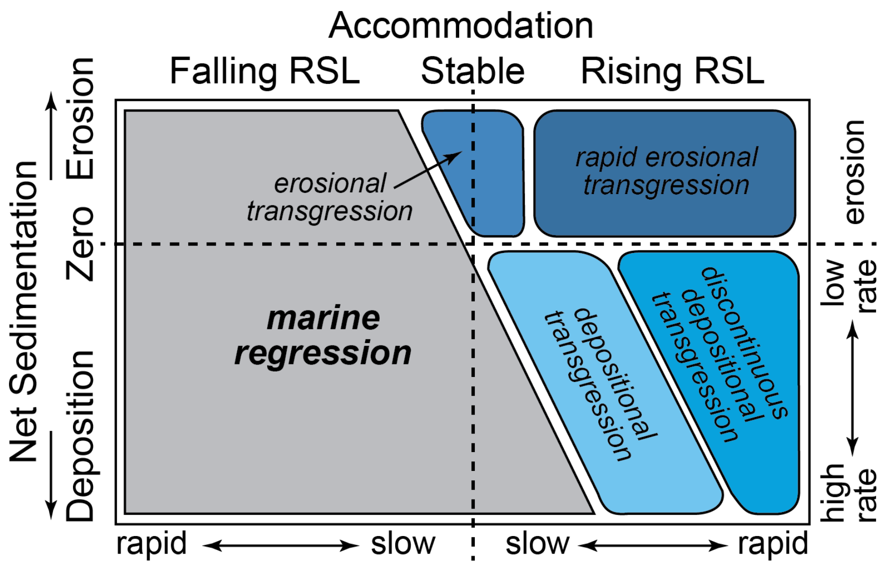


**Figure 1.** Marine transgression as a function of accommodation creation (stable to rapidly rising sea level) and net sediment deposition. Modified from Curray (1964).

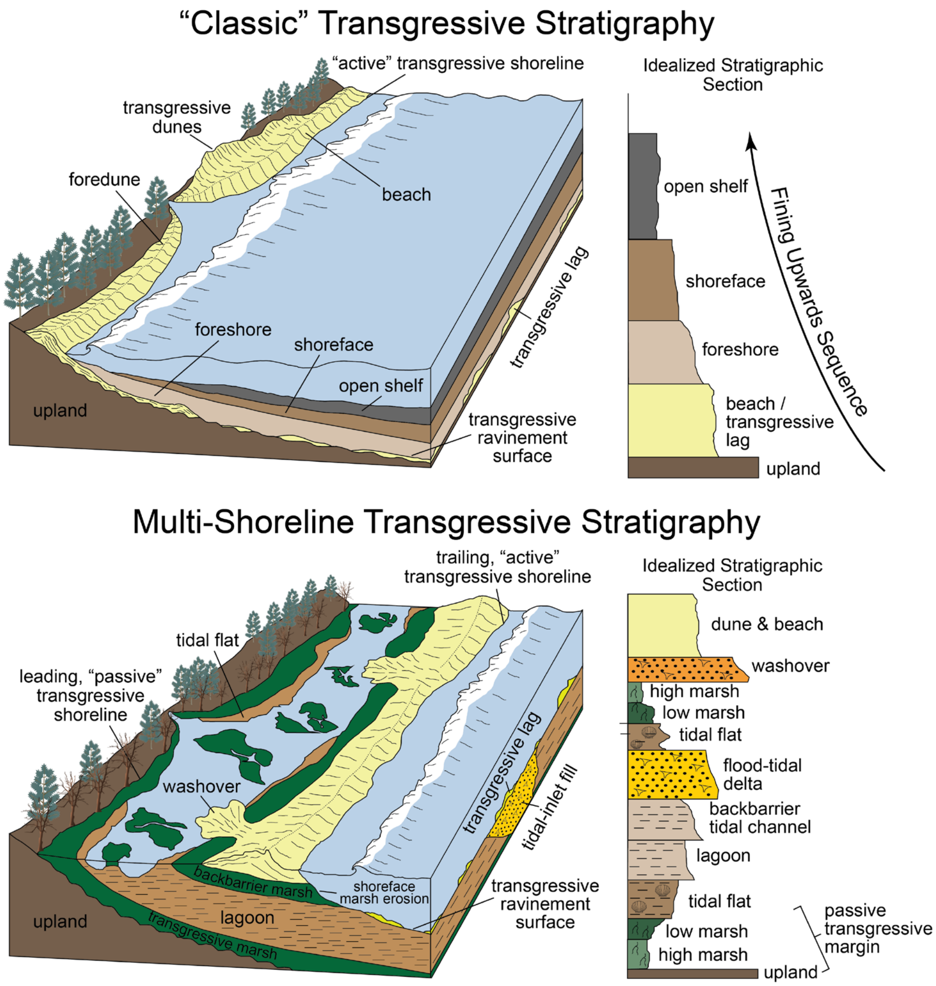


**Figure 2.** Transgressive succession in (a) simplified fining-upward form along open-ocean coasts; and (b) with more complex (and realistic) facies stacking patterns along barrier-island coasts characterized by both active, trailing-edge and passive, leading-edge transgressive shorelines.

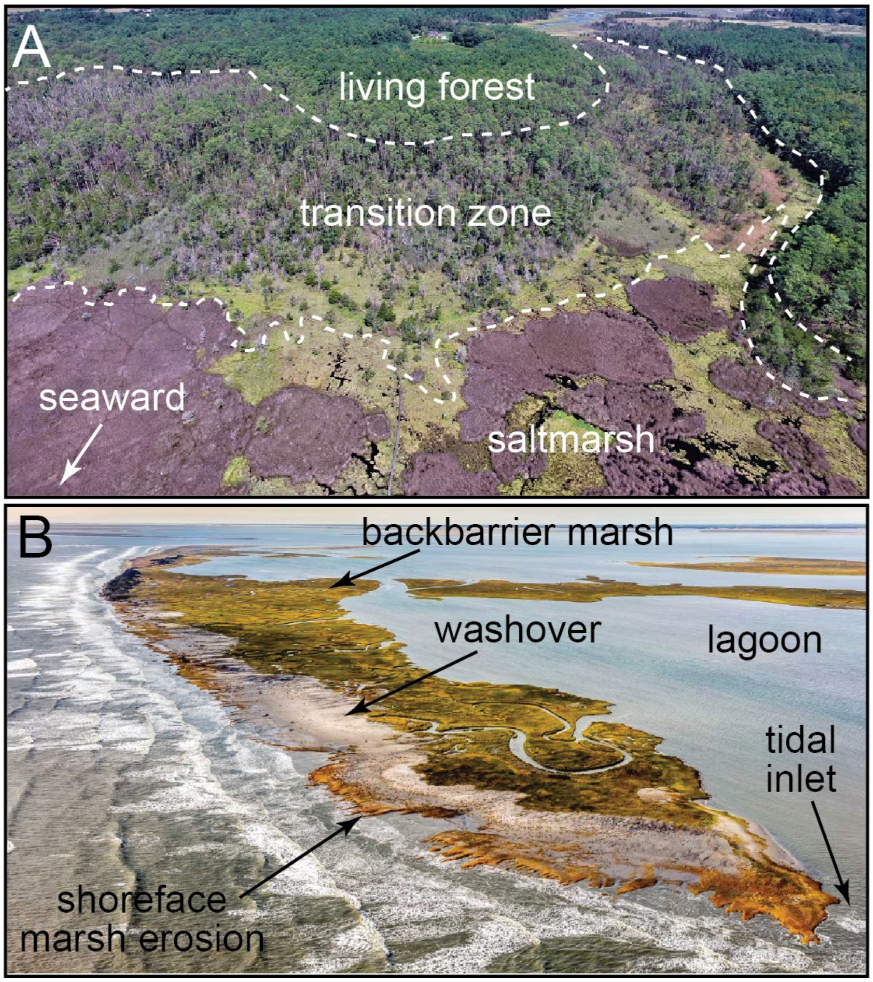


**Figure 3.** Examples of modern marine transgression in the form of (a) changes in vegetation distribution along a passive marsh-upland transgressive margin, highlighting a “ghost forest” transition zone with dead and stressed trees (Phillips Creek, Virginia, USA); and (b) burial and shoreface erosion of backbarrier saltmarsh by an actively transgressing, landward-migrating barrier island (Cobb Island); both along the rapidly transgressing Virginia Eastern Shore, USA. Image credits: T. Messerschmidt (a) and G. Campbell, At Altitude Gallery (Cape Charles, Virginia) (b).

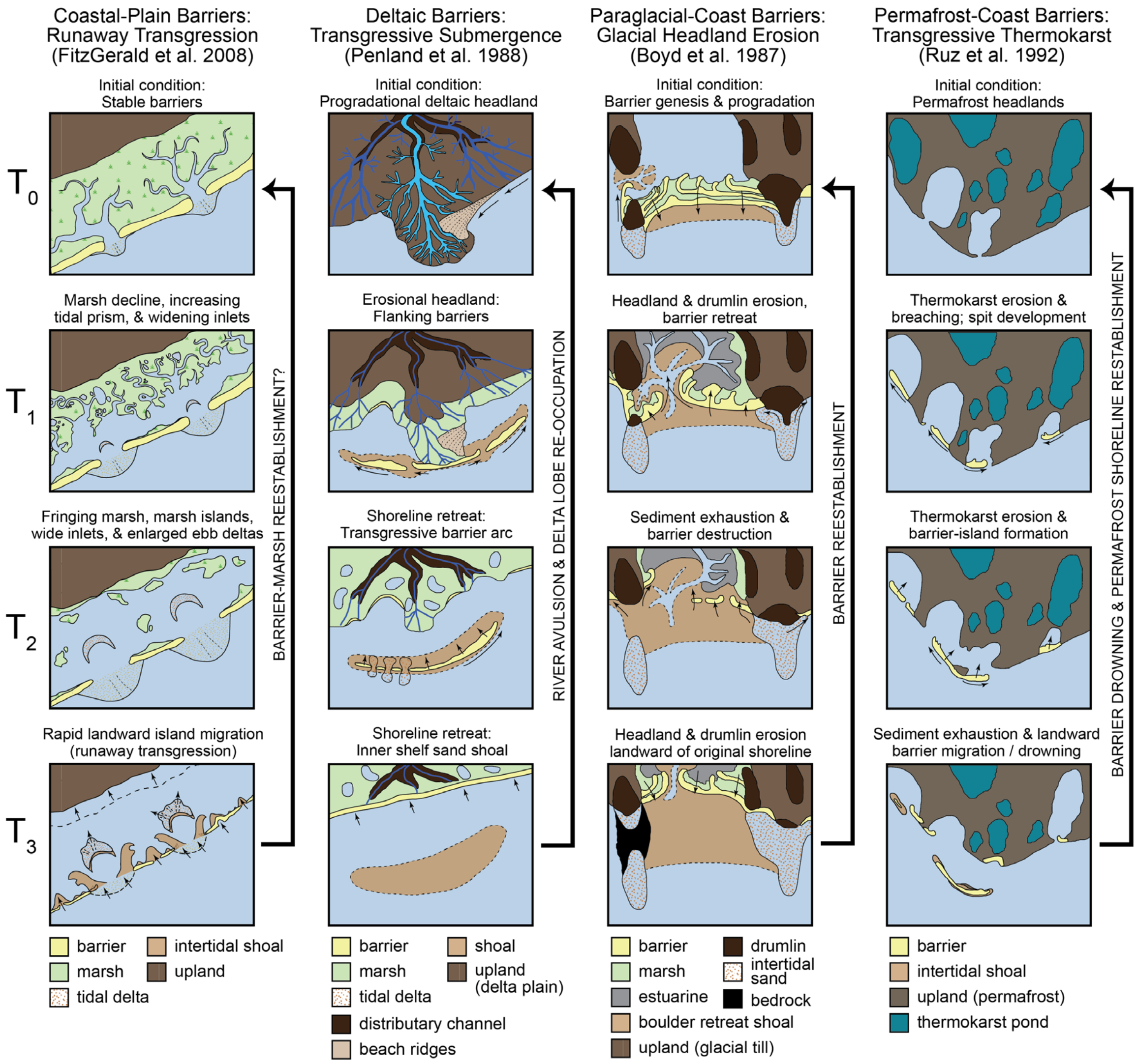


**Figure 4.** Models of punctuated transgression in response to increasing accommodation in active coastal settings. Following catastrophic collapse in the "Runaway Transgression" model (left), barriers may re-establish upslope, closer to the mainland, where tidal prism is lessened due to the smaller backbarrier area, or may be lost entirely (FitzGerald et al. 2018). In deltaic, paraglacial, and thermokarst coastal settings, rapid backstepping and barrier drowning is cyclical, and associated with exhaustion of local sediment reservoirs from deltaic headlands, glacial deposits, and eroding permafrost, respectively. Figure parts are modified from (left to right) FitzGerald et al. (2008), Penland et al. (1988), Boyd et al. (1987), and Ruz et al. (1992), respectively.

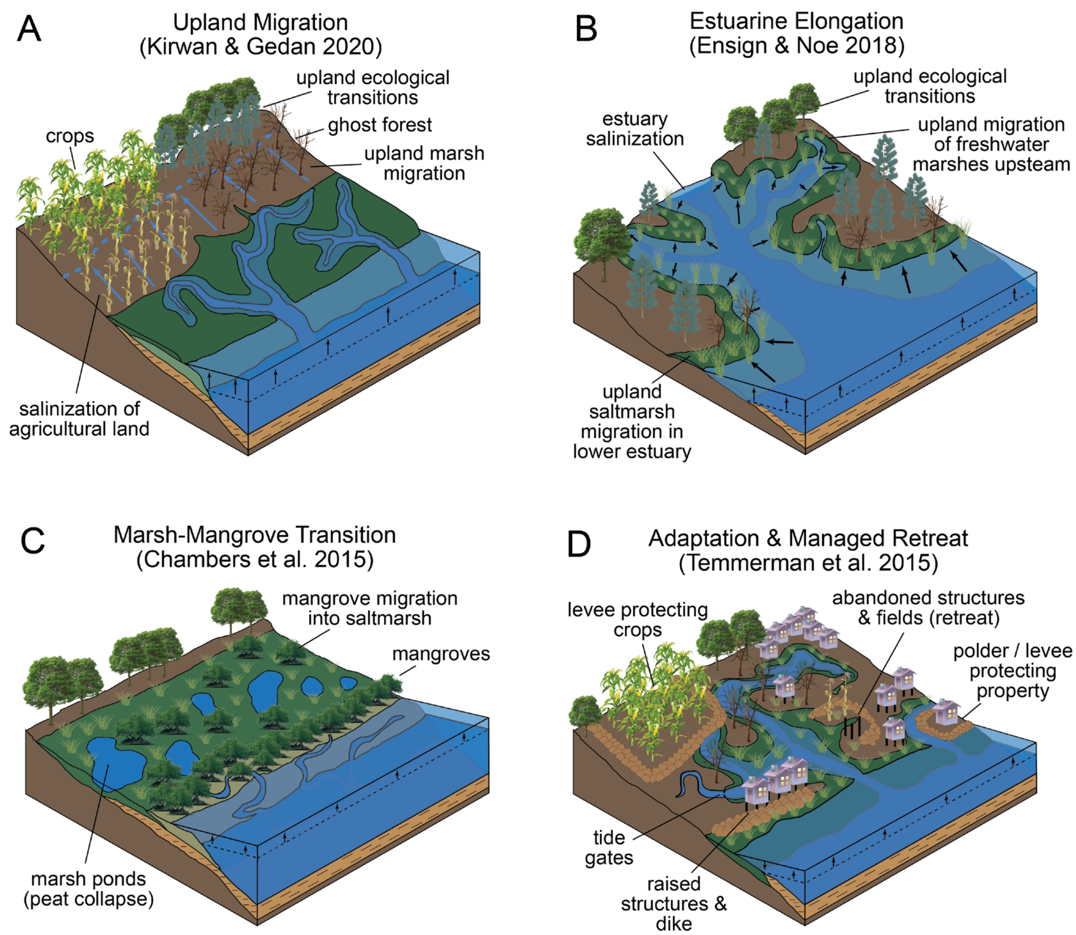


**Figure 5.** Styles of passive transgression. a) saltmarsh migration into upland, terrestrial ecosystems including forests and farmland. b) elongation and salinization of estuaries, leading to the replacement of forested wetlands by freshwater marshes, and the replacement of freshwater marshes by salt marshes, c) migration of mangroves into landward marshes, which may be accompanied by peat collapse, d) managed retreat resulting in replacement of upland land uses by saline marshes.

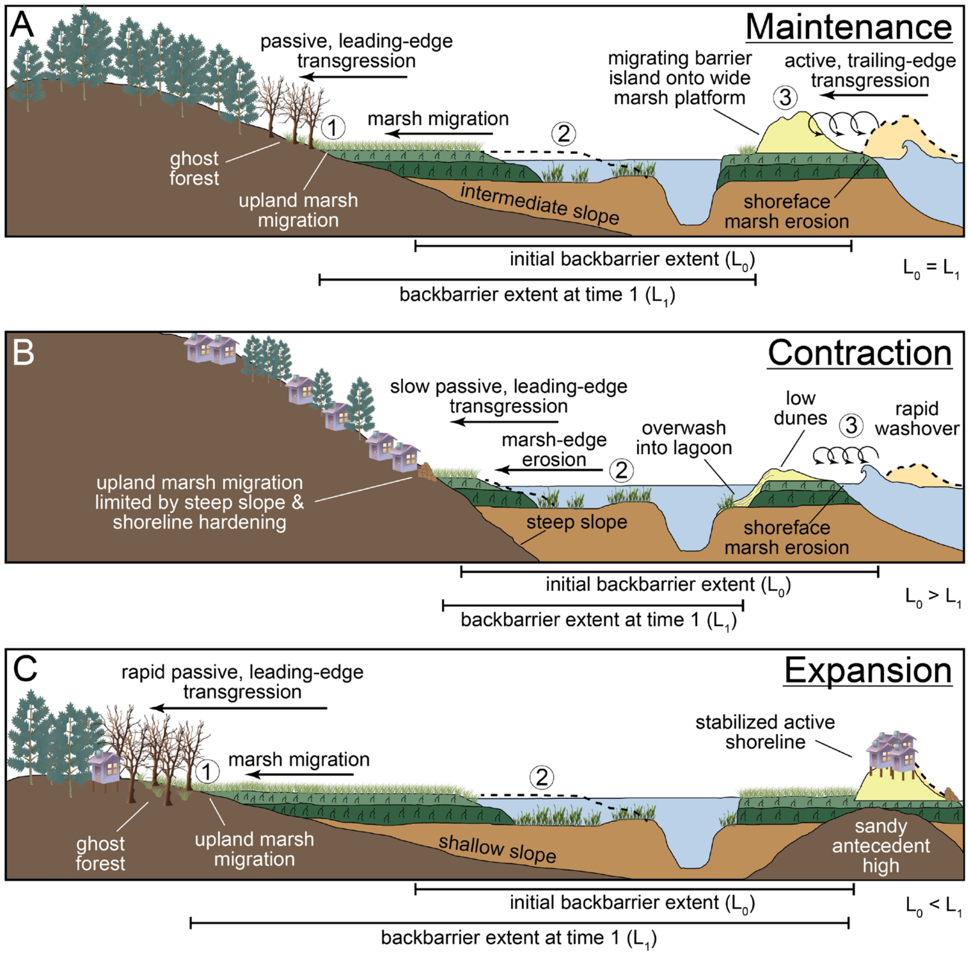


**Figure 6.** Competition between co-evolving passive transgression at the leading, upland margin, and active transgression at the trailing, seaward margin can lead to the (a) maintenance, (b) contraction, or (c) expansion of the coastal zone. Marshes migrate into terrestrial ecosystems and forested wetlands at rate proportional to topographic slope (1), whereas factors such as sediment supply, slope, and biophysical feedbacks control the rate of overwash, burial of intertidal ecosystems, and attendant barrier-island migration at the open-ocean shoreline (3). Between these margins, erosion, submergence, and/or accretion of intertidal environments can lead to backbarrier ecosystem transitions (2). Coastal infrastructure at the seaward margin favors expansion by reducing island migration, but infrastructure at the landward margin favors contraction by reducing marsh migration.

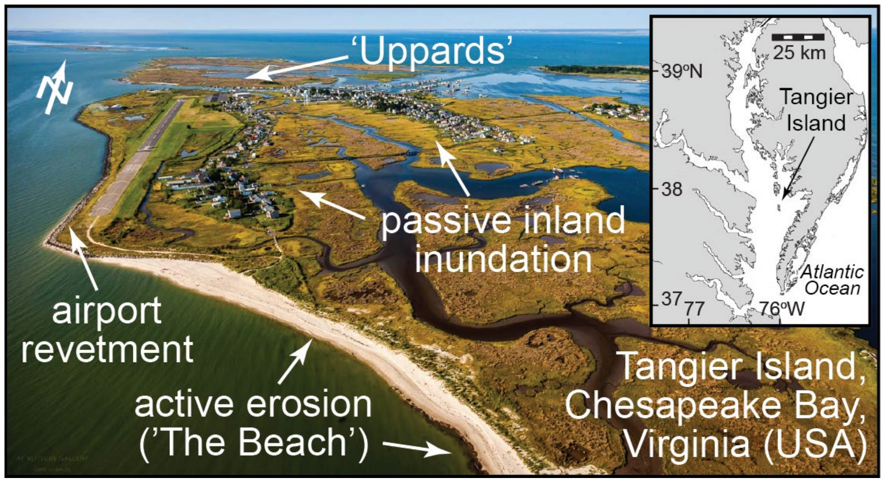


**Figure 7.** Aerial view of Tangier Island (Chesapeake Bay, Virginia, USA). Image credit: G. Campbell, At Altitude Gallery (Cape Charles, Virginia) (with permission).