

Coastal wetlands, sea level, and the dimensions of geomorphic resilience

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ABSTRACT

Geomorphic system resilience is often perceived as an intrinsic property of system structure and interactions but is also related to idiosyncratic place and history factors. The importance of geographical and historical circumstances makes it difficult to generate categorical statements about geomorphic resilience. However, network-based analyses of system structure can be used to determine the dynamical stability (= resilience) based on generally applicable relationships and to determine scenarios of stability or instability. These provide guidelines for assessing place and history factors to assess resilience. A model of coastal wetlands is analyzed, based on interactions among relative sea level, wetland surface elevation, hydroperiod, vegetation, and sedimentation. The system is generally (but not always) dynamically unstable and non-resilient. Because of gradients of environmental factors and patchy distributions of microtopography and vegetation, a coastal wetland landscape may have extensive local variations in stability/resilience and in the key relationships that trigger instabilities. This is illustrated by a case study where dynamically unstable fragmentation is found in two nearby coastal wetlands in North Carolina's Neuse River estuary—Otter Creek Mouth and Anderson Creek. Neither is keeping pace with relative sea level rise, and both show unstable state transitions within the wetland system; but locally stable relationships exist within the wetland systems.

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1. Introduction

Resistance is the ability of a geomorphic system to withstand or absorb a change or disturbance with minimal alteration. The system's ability to recover to or toward its predisturbance state is termed *resilience*. Resilience is closely linked to dynamical stability and is often thought of as controlled by the intrinsic structure and dynamics of the system. However, like geomorphic characteristics in general, resilience is controlled by three sets of factors: laws, place, and history. The purpose of this paper is to explicitly link aspects of resilience to general or universal factors vs. geographically and historically contingent factors. While the law, place, and history framework will be familiar (though perhaps using other terms) to virtually all geomorphologists and geomorphology students, the relative importance and influence of these are rarely explicitly considered.

Resilience can be assessed in several ways. These include observations or monitoring of geomorphic responses to disturbances or change (e.g., Fryirs et al., 2015) or historical reconstructions thereof (e.g., de Oliveira et al., 2008). Simulation modeling is also used (e.g., Wang and Temmerman, 2013), as well as assessments of traits or resources critical for recovery toward predisturbance conditions (e.g., Raposa et al., 2016). The focus here is on resilience as indicated by dynamical stability. Stable systems are insensitive to small changes and disturbances and

recover toward the predisturbance state afterwards. In dynamically unstable systems the effects of small perturbations persist and grow, and the predisturbance state is not recovered. Thus dynamical instability indicates resilience. While dynamical stability is often assessed based on mathematical models, in geomorphology these can be derived from, linked to, and tested via observational and historical data (Phillips, 1999a, 2015). Dynamical stability is discussed further in Section 2.2.

1.1. Laws, place, history

Laws are the general principles and relationships applicable to any type of geomorphic system (e.g., rivers, karst caves, permafrost, hillslopes) anywhere and anytime. These dictate aspects of resilience such as the reversibility of geomorphic changes, dynamical stability related to system structure, and rates of physical and chemical processes. In fluvial systems, for example, fluid transport laws dictate the complex interactions among hydraulic variables, energy dissipation in mass transport, and potential rates of, e.g., erosion and mass flux. Laws may be universal laws per se, such as mass and energy conservation, or other general principles, relationships, or representations applicable to (e.g.) fluvial systems in general regardless of location, environmental context, or time frame.

Place factors are characteristics of the local and regional environment such as climate, geology, tectonics, and biotic traits that provide context and limits for the applicable laws. For example, chemical kinetics of calcite dissolution are applicable to any karst system, but the

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actual rate and nature of dissolution is constrained by lithology, rock structure, hydroclimatology, biotic processes, and other geographical factors. Place factors such as rock or soil strength, absorption capacities, and risk climatology (the regime of disturbances, climatic and otherwise) often determine resistance. Others, such as resources for recovery (e.g., sediment supply, biotic potential, or capital) and degrees of freedom or constraint for geomorphic responses, are critical to resilience.

Historical factors such as initial conditions at the time of disturbance and proximity to thresholds are key determinants of vulnerability and are influenced by longer-term developmental trajectories and recent event histories. History may also interact with place factors via the developmental stages or trajectories of, e.g., vegetation or climate, and with laws via changes in system structure. Geomorphic responses to disturbances are strongly conditioned by timing, event sequences, and initial conditions, for instance. Resistance and resilience may also differ according to the stages of, e.g., vegetation succession, regolith development, or filling of sedimentary accommodation space.

Categorical statements about geomorphic resilience of types of geomorphic systems must be based on those aspects related to laws (see, e.g., [Raposa et al., 2016](#)). Because of the importance of local geographical and historical circumstances, it is difficult to make broad generalizations. For instance, [Long et al.'s \(2006\)](#) study of geomorphological resilience of a coastal landscape in Britain found that the observed resilience over 5 ka is attributable largely to abundant sediment supply and three large tidal inlets that moderated sediment supply and distribution. [Long et al. \(2006\)](#) also concluded that the concept of coastal resilience is dependent on a clear spatial and temporal context. Similarly, [Fryirs et al.'s \(2015\)](#) study of fluvial system resilience to catastrophic flooding found that the particulars of long-term geomorphic history, short-term flood event characteristics, and the environmental setting were crucial. These concepts will be explored in more detail in the context of coastal wetland systems.

1.2. Coastal wetlands and sea level

Coastal wetlands such as salt marshes provide enormous economic and aesthetic values to humans and numerous ecosystem services. They also play key geomorphological roles in, e.g., sediment storage and buffering inland areas from storm impacts. As low-elevation coastal landforms, coastal wetlands are inherently vulnerable to coastal submergence because of relative sea level rise. As ecotones, coastal wetlands may be sensitive to, and have impacts on, estuarine and coastal systems at lower elevations and upland landscapes at higher positions. The most fundamental factor in determining wetland survival is the ratio of accretionary upbuilding to relative sea level rise. However, numerous other geomorphic, hydrologic, and ecological factors and interactions influence the response of existing wetlands to sea level rise and the ability for new wetlands to form. Vulnerability and resilience of coastal wetlands to sea level rise may often be over- and underestimated, respectively, because biogeomorphic feedback relationships known to promote accretion and inland migration are not considered (e.g., [Kirwan et al., 2016](#); [Raposa et al., 2016](#)).

Examples of law, place, and history factors applicable to coastal wetlands are given in [Table 1](#).

The relationship between sedimentation and vegetation illustrates the influence of local place factors on general laws. The influence of mineral sediment input on plants is universal in the sense of wetland plants being generally unable to tolerate complete burial. Yet wetland plants are often positively influenced by more moderate deposition rates (e.g., [Reed, 1990](#); [Morris, 2006](#); [Corenblit et al., 2015](#)), and [Walters and Kirwan \(2016\)](#) identified a threshold depositional thickness for beneficial vs. deleterious effects for *Spartina alterniflora*. However, the details of these responses may be quite variable among hydrophytes (e.g., [Dexter, 1981](#); [Roman et al., 1984](#); [Phillips, 1987](#); [Mendelssohn and Kuhn, 2003](#); [Corenblit et al., 2015](#)).

Table 1

Examples of law, place, and history factors in coastal wetlands.

Factors	Coastal wetland examples
Laws	Interrelationships among sea level, hydroperiod, sedimentation, vegetation productivity, and wetland surface elevation
Place: climate	Presence/absence & persistence of ice; tropical features (mangroves, coral reefs); storm climatology
Place: topographic & hydrographic setting	Elevation & slope of adjacent uplands; estuarine & deltaic circulation & sedimentation patterns; salinity; tidal range; fluvial vs. tidal vs. wave influence
Place: biogeography	Gradients of edaphic factors (e.g., flooding, soil saturation, salinity, wave exposure); local/regional species composition & potential seed sources; dispersal mechanisms
History: storms	Storm magnitude, frequency, timing; sequence of events; time since last storm event
History: relative sea level	Direction & pace of eustatic sea level change; land surface uplift/subsidence trends
History: age	Time for development of landforms, sedimentary environments, biotic communities

Sea levels rise and fall over longer periods, but the focus here is on rising sea level, representing the Holocene and contemporary trends, with likely acceleration in the near future. The principles here apply to freshwater and mangrove swamps as well as salt, brackish, and freshwater marshes, but the focus here will be on marshes.

The key system components common to wetlands in general that must be considered in this context are relative sea level change (eustatic sea level rise plus or minus any subsidence or uplift on land), wetland surface elevation, net vertical accretion (upbuilding minus any erosional removal, autocompaction, or subsidence), deposition (of mainly inorganic sediment), vegetation growth and production, and hydroperiod. The latter refers to the hydrologic regime with respect to the frequency and duration of inundation. If surface elevation is increasing at a rate comparable to relative sea level rise (SLR), the wetland can potentially remain stable during SLR. If the elevation does not increase, or does so at a rate < SLR, a net loss will occur owing to erosion and drowning. Loss is a common trend in coastal wetlands around the world at present ([Orson et al., 1985](#); [Fitzgerald et al., 2008](#); [Wang and Temmerman, 2013](#)). If upbuilding exceeds SLR (usually on account of large sediment inputs), wetlands may expand despite SLR (e.g., [Froemer, 1980](#); [Rosen and Xu, 2013](#)).

Numerous feedback relationships exist among the components above. If relative SLR is greater than the wetland surface elevation increase, the hydroperiod increases owing to more frequent and longer inundation. This, in turn, tends to increase sediment deposition rates. Hydroperiod and deposition influence vegetation cover and productivity, either positively or negatively, depending on the vegetation type, magnitude or rate of change, and local ecological factors such as salinity and the redox environment. Vegetation promotes deposition via sediment trapping and also contributes independently to vertical accretion because of inputs of organic matter. Net vertical accretion is obviously directly related to wetland surface elevation. These interactions are described in greater detail by, e.g., [Reed \(1990, 2002\)](#), [French \(2006\)](#), [Nyman et al. \(2006\)](#), [D'Alpaos \(2011\)](#), [Kirwan et al. \(2012\)](#), [Passeri et al. \(2015\)](#), and [Walters and Kirwan \(2016\)](#).

Factors mentioned above are by no means the only ones that influence wetland erosion, accretion, and geomorphic and ecological dynamics. Individual storms, storm climatology, human and other faunal impacts on wetland vegetation, variations in sediment sources and inputs, and neotectonics, among many other factors, are important influences in many cases (e.g., [Phillips, 1989](#); [French, 2006](#); [Kim et al., 2013](#); [Kim, 2014](#); [Mariotti and Fagherazzi, 2013](#); [Escapa et al., 2015](#)). In a systems analysis context, however, these can be viewed as external effects on the components listed above in the sense that no feedback relationships exist from wetland geomorphology to, e.g., storm wave regimes. Thus, these external influences do not affect system dynamical stability.

More generally, these external variables are place and history factors that apply to specific cases but not to the general model.

2. Network model of coastal wetland system interactions

2.1. Wetland response to sea level

The literature on coastal wetland response to sea level change reflects general agreement that six key components are applicable to all cases:

- Relative sea level, incorporating eustatic sea level rise plus or minus any uplift or subsidence of the wetland area.
- Hydroperiod, indicating the frequency and duration of wetland surface inundation.
- Deposition of dominantly mineral, inorganic sediment.
- Vegetation cover and biomass production (including organic matter deposition).
- Net vertical accretion: upbuilding from deposition and organic matter accumulation minus autoconsolidation or local subsidence.
- Surface elevation relative to sea level.

Interactions among these components are shown in Fig. 1 and Table 2. Positive relationships indicate that a change (increase or decrease) in the component at the beginning of an arrow (Fig. 1) results in a change in the same direction in the component at the end of the arrow, other things being equal (as other interactions are accounted for by other links). For example, an increase or decrease in hydroperiod is associated with an increase or decrease in deposition. Negative links indicate that a change in the source component leads to a change in the component at the end of the arrow in the opposite direction. An increase (decrease) in relative surface elevation, for instance, leads to a decrease (increase) in hydroperiod.

Many of the relationships in Fig. 1 and Table 2 are always either positive or negative, but some may work either way. Hydroperiod effects on plants may either stimulate or reduce vegetation cover and productivity, depending on the species involved, stage of wetland development or deterioration, and the degree of change in inundation. Vegetation may be self-enhancing because of effects on substrate stability, soil nutrients, and propagule sources or may be self-limiting owing to density dependent effects such as resource competition. The focus here is marshes that may experience lateral (i.e., fringe or shoreline) erosion but not surface erosion or vertical truncation. However, such cases could be incorporated by considering surface erosion and truncation as negative deposition and negative vertical accretion, respectively.

Relationships in Fig. 1 can be depicted as a 6×6 interaction matrix **A** with cell entries of -1 , 0 , or 1 depending on the direction of the links. The system is dynamically stable and resilient if the real parts of all the complex eigenvalues λ_i , $i = 1, 2, \dots, N$ ($N = 6$ in this case) are negative. Because $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_N$, the criterion is satisfied if $\lambda_1 < 0$. Testing the effects of different relative strengths of the interactions can be accomplished numerically by varying the absolute value of the nonzero entries in the range of $0 < a_{ij} \leq 1$. A more complete discussion of this

Table 2
Coastal wetland system interactions.

Link	Direction	Explanation
Hydroperiod → deposition	Positive	Delivery of inorganic sediment to marsh surface; suspended sediment settling time
Hydroperiod → vegetation	Positive or negative	Depends on vegetation characteristics, extent of inundation, & soil chemistry
Deposition → net vertical accretion	Positive	Accretion from sediment deposition
Deposition → vegetation	Positive or negative	Positive: nutrient inputs Negative: burial
Vegetation → deposition	Positive	Sediment trapping; flow energy dissipation
Vegetation self-effects	Positive or negative	Positive feedbacks from seed source effects or ecosystem engineering; negative feedbacks from density dependence, resource limitations, allelopathy
Vegetation → net vertical accretion	Positive	Organic matter inputs
Net vertical accretion self-effects	Negative	Autoconsolidation
Net vertical accretion → relative surface elevation	Positive	Upbuilding (or subsidence)
Relative surface elevation → hydroperiod	Negative	Lower relative elevation leads to more inundation
Relative surface elevation → relative sea level	Negative	Higher or lower surfaces relative to mean water levels
Relative sea level → hydroperiod	Positive	Increase flooding frequency & duration during relative SLR

type of stability analysis applied to geomorphic and ecological systems is given by Logofet (1993) and Phillips (1992a, 1999a).

2.2. Stability analysis

Eigenvalues for an interaction matrix based on Fig. 1 were determined for all combinations of positive and negative links for entries that could be either and by varying the absolute values of the nonnegative entries to reflect two orders of magnitude (hundredfold) difference in the relative importance of various process interactions. The latter variations were generally insufficient to change the sign of λ_1 , though they did make a difference in its absolute value, which indicates the rate of divergence (or convergence) following a change or disturbance.

Most configurations resulted in $\lambda_1 > 0$, indicating dynamical instability. This indicates that changes from, e.g., storms, sediment supply, vegetation invasions or destruction, etc., are likely to persist and grow over (a finite) time, resulting in a new system state. In earlier studies in New Jersey, this was shown to be correlated to increasing divergence of initially more uniform wetland surfaces into more complex spatial mosaics of high marsh, low marsh, tidal flats, salt pans, and open water (Phillips, 1986, 1989). Model studies (Phillips, 1992a; D'Alpaos, 2011) have suggested that this is likely to be a general phenomenon.

Also, marsh fragmentation and increasing spatial complexity has indeed been documented in a number of field studies, independent of stability models (e.g., Pethick, 1974; Boston, 1983; Nyman et al., 1993, 1994; Hackney et al., 1996; van Wesenbeeck et al., 2008; Kim et al., 2009). Note that instability does not necessarily indicate net loss of wetlands but that the state of the wetland changes—though where fragmentation includes a significant increase in open water, a net loss typically occurs.

The system can be stabilized, however, where the hydroperiod-to-vegetation and vegetation self-effect links are negative and where the deposition-to-vegetation link is negligibly small (or zero). In these configurations the (real part of) the largest eigenvalue is negative, and the system is dynamically stable and resilient. The latter is plausible in

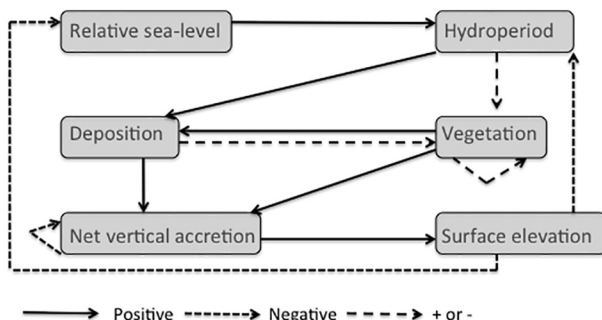


Fig. 1. Coastal wetland system feedbacks.

relatively sediment-starved situations and/or where plants are insensitive to the relevant range of deposition rates and amounts. Determining the circumstances under which different system configurations occur directly links geomorphic resilience to geographically and historically contingent factors.

The different potential configurations of the wetland system may not only differ between coastal landscapes but also within a landscape and over time as conditions—and thus the direction or importance of some of the links—change. This is illustrated with a case study below.

3. Case study—Neuse Estuary, North Carolina

3.1. Study area

Two study sites in the Neuse River estuary system, North Carolina, are used here. Otter Creek mouth (OCM) is a small wetland complex at the mouth of Otter Creek, a drowned tributary of the Neuse River estuary, part of the Pamlico-Albemarle Sound estuarine complex (Fig. 2). The brackish water system includes saw-grass (*Cladium jamaicense*) and black needlerush (*Juncus roemerianus*) along with other marsh grasses, shrubs such as marsh elder (*Iva frutescens*), and scattered trees, with bald cypress (*Taxodium distichum*) in the wetter and red cedar (*Juniperus virginiana*) on drier patches. At this site a clear distinction exists between fringe marsh at lower elevations dominated by *Juncus* and higher marsh dominated by *Cladium*. Cypress occurs in fringe and in high marsh, with the other woody species occurring in higher sites. An overview of wetland response to sea level in North Carolina is given by Moorhead and Brinson (1995).

Anderson Creek (AC) is an arm of Slocum Creek, another drowned Neuse Tributary. It flows approximately parallel to the Neuse with a

continuous marsh fringe from its mouth, grading to a cypress-gum swamp fringe upstream. There is not a clear distinction between low and high marsh but rather a mosaic of higher/relatively drier and lower/wetter patches. Saw-grass is the dominant species, with black needlerush and cattail (*Typha angustifolia*) also occurring, along with scattered cypress, cedar, and marsh elder. Uplands are a mixed pine (*Pinus taeda*) and oak (*Quercus* spp.) dominated forest.

The Neuse estuary is a part of the Pamlico Sound estuarine system. The drowned river valley is shallow, poorly flushed, and oligohaline. In the study area the river is about 6 km wide, with a maximum depth of about 4 m. The climate is humid subtropical, and the upland vegetation is generally pine, mixed hardwood (typically oak dominated), or pine/hardwood forest.

3.2. Methods

The study areas were visited numerous times in the field over the period 1990–2015, and vegetation cover and observed changes in surficial soil/sediment characteristics, geomorphic features, and appearance/disappearance or growth/reduction in surface areas were recorded. In particular, the geomorphic indicators shown in Table 3 were assessed. The most comprehensive field examinations occurred in 1993–96 and 2012–15 (OCM), and 1990–97 (AC).

Vegetation assessment focused on the presence and distribution of black needlerush, saw-grass, cattail, marsh elder, bald cypress, and red cedar. Assessments also looked for presence of plants indicating higher salinity levels, such as several species of *Spartina* marsh grass or *Salicornia* glassworts, but these were not found at the field sites.

Black needlerush is tolerant of salinity and frequent inundation and typically occurs along banks and shorelines, and on substrates ranging

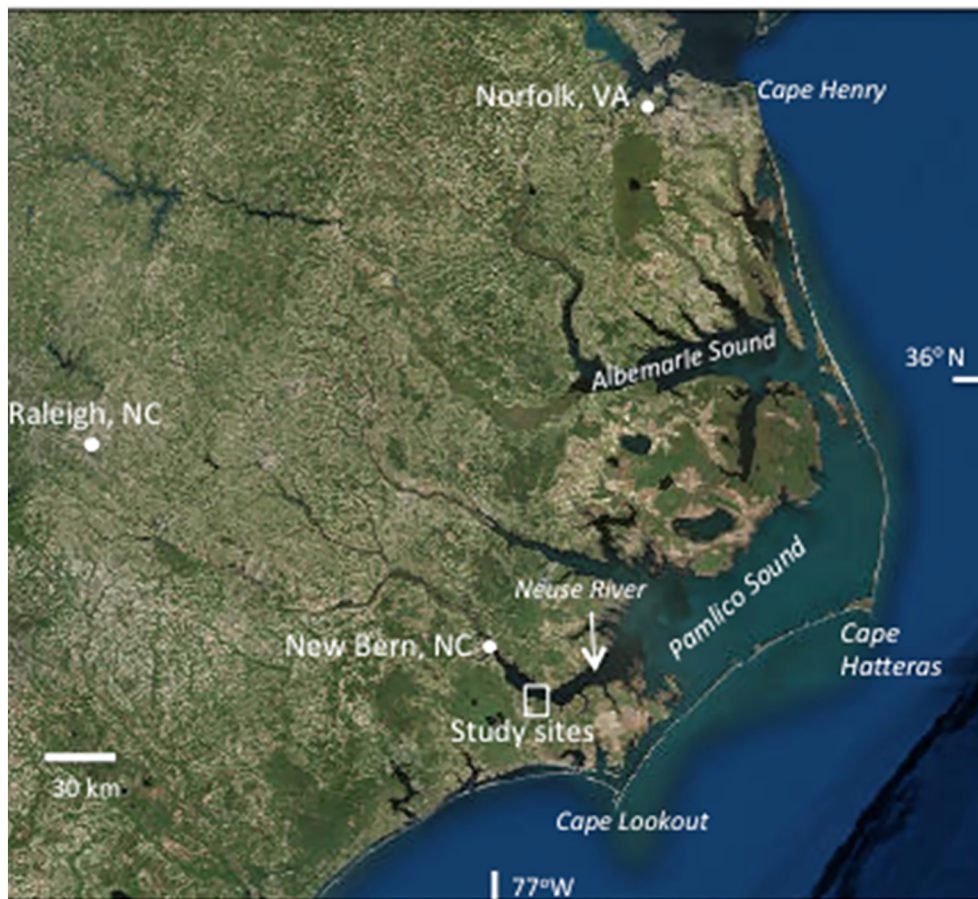


Fig. 2. Study area.

Table 3
Field geomorphic indicators.

Indicator	Inferred process or change
Vegetation type & distribution	Salt & flooding tolerance
Vegetation burial	Sand deposition
Exposed root mats	Surface erosion
Erosion scarps	Shoreline erosion
Soil stratigraphy (hydric soil onlapping non-hydric upland soil)	Wetland encroachment on upland
Sediment/substrate (sand vs. mud vs. peat)	Depositional environment
Wrack	Storm inundation

from sand to organic clays. Saw-grass occurs in brackish and freshwater settings and in frequently flooded areas, but is less tolerant of salinity and flooding than *Juncus*. Cattails are less tolerant of salinity than saw-grass, but may occur where water levels are generally higher. Marsh elder, a shrub, occurs in higher areas of salt and brackish marshes, and is not as flood tolerant as the grasses above. Red cedar occurs only on the higher areas. While it is a common colonizer of disturbed sites, in this dynamic coastal context it indicates at least short term stabilization of features such as sand ridges. Bald cypress trees germinate in wet but not permanently flooded, exposed sites—in the study area, river and creek banks. Once established, however, they can tolerate standing water. Their distinctive roots and buttresses often persist well after tree death, indicating approximate former shoreline and bank positions.

Vegetation burial was noted where recent sediment deposits overlaid or partially covered still-living or undecomposed plants. Exposed root mats indicate recent (post plant establishment) erosion. These occurred in both ground-surface exposures, and as root overhangs on eroding banks or shores. Erosion scarps were recognized as unvegetated (other than exposed roots) vertical, steep concave, and overhanging banks. Wrack (mainly vegetation debris but including some anthropic trash) occurs both on the ground surface, and off the ground, in trees and shrubs. Wrack indicates a minimum high water level from storms.

Dominant substrate type is a general indicator of depositional and energy environments, though it is also influenced by sediment sources and vegetation. Dominantly sand occurs in areas subject to significant estuarine wave energy, or where erosion of nearby upland bluffs or cliffs with loamy sand or sandy loam textures occurs. Silt-clay muds indicate lower-energy settings. Peaty substrates indicate well-established marsh (in this area, mainly *Cladium*). Where wetlands are encroaching on adjacent uplands, the soil stratigraphy often indicates this. These situations are characterized by hydric layers (generally muddy and peaty material) overlying mineral soil with colors (yellow, brown, red, or orange) indicating oxidation in a previously unsaturated setting. In the field the hydric layers were recognized mainly on the basis of Munsell chromas ≤ 2 .

Aerial photography was also used to identify changes. Photographs of sufficient resolution are available for March 1993; January 1998; September 2002; February 2007; May 2011; March 2013; and April and July 2014. Photographs were accessed via Google Earth™. Sequential photographs were assessed for changes in the location and extent of the following geomorphic or ecological features: Marsh, upland forest, sand ridges, open water, interior ponds, mud flats, and cypress swamp.

Observed changes were recorded in terms of transitions among geomorphic units—for example, conversion of low or fringe marsh to open water via shoreline erosion. These were interpreted in terms of the driving processes, and represented as a directed graph. The spectral radius of the graphs was determined as an indication of the complexity of the network of transitions (for a full discussion of algebraic graph theory methods in geomorphology see Phillips, 2014; Heckmann et al., 2015).

The pattern of observed state-changes was then interpreted as a chronosequence, whereby the existence of a given state or geomorphic unit either facilitates, inhibits, or has negligible direct influence on the other states. Thus, for instance, presence of a mudflat may facilitate conversion to marsh (via accretion and vegetation establishment) or open

water (via substrate erosion and drowning). A sand ridge, by contrast, inhibits conversion to marsh owing to the higher elevation and consequently reduced hydroperiod. The path stability of these sequences (robustness) was then determined using methods developed by Phillips (2015), which are mathematically identical to those applied to the general wetland response model.

Note that while some methodological overlap exists, three distinctly different types of system/network analysis are employed here. The first is a stability analysis of the general relationships involved in coastal wetland response to SLR, indicating whether such systems tend to be resilient to perturbations in any system component (for example, vegetation change or acceleration or deceleration of SLR). The second examines the specific observed state transitions at the study sites to assess changes in complexity. The third is an analysis of the observed transitions with respect to stability of the pathways of change; the tendency to maintain a developmental pathway or mode of operation in the presence of environmental fluctuations (Phillips, 2015).

3.3. Results

At OCM, six major changes were observed over the study period (Table 3; Fig. 3). First, shoreline erosion and formation of a sand beach occurred on the left (west) bank of the mouth of Otter Creek. Second, the northwest tip of OCM was eroded, isolating a bald cypress tree in shallow water. Third, upward/inland extension of the fringe marsh occurred, especially on the Neuse side of OCM. Fourth, two embayments experienced erosional enlargement: converting wetland to open water and isolating some cypress trees in standing water. Fifth, a small sand ridge developed in the center of OCM, subsequently colonized by vegetation. Finally, a bald cypress tree became established along the back shoreline (southeast section of OCM). This is significant because the tree and its partially aerially exposed roots and buttresses can form (as in this case) a significant biogeomorphic feature resistant to erosion.

In the case of the first change, the key instability is the deposition-vegetation links. Here Hurricane Bertha in 1996 resulted in erosional stripping at the water's edge and slope failures of the bluff shorelines, delivering a large amount of sand. Vegetation destruction by the storm resulted in the persistence of the feature because of reduced sediment trapping and erosion protection, leading to the transformation of the original shoreline (fully vegetated with no sand beach) to its current state by about 2008.

With respect to erosion on the northwest point and isolation of the cypress, gradual erosion isolated the tree around 2010, with full separation even at low water soon following. At this stage the interactions can be represented as shown in Fig. 4A. The hydroperiod to vegetation link is largely irrelevant, as mature established cypress can survive in perpetually flooded conditions. The vegetation self-effects are also negated (cypress cannot germinate in permanently flooded conditions). Deposition effects on the tree can be considered irrelevant in the short term (~10 years) or positive in the long term (continued erosion = negative deposition = inhibition of tree health). Enlargement of the two embayments appears to result from storm erosion disturbances of vegetation, which further exacerbates erosion, resulting in net vertical truncation. This decreases relative surface elevation and increases hydroperiod, which in this case inhibits vegetation (Fig. 4B).

The expansion of the marsh fringe is consistent with relative sea level rise, and the conversion to marsh on the upper edge probably related to increasing hydroperiod, which favors *Juncus* at the expense of other species.

In the stable areas in the OCM interior, the inferred relationships are as shown in Fig. 5. The deposition-to-vegetation link is negligible or missing because deposition here has not been large enough to bury or suppress vegetation and does not provide significant nutrient inputs. This is one of the stable configurations, reflected in the persistence of this state throughout the study period.



Fig. 3. Geomorphic changes, Otter Creek Mouth, 1990–2015 (base image, 2014, Google Earth™).

In the Anderson Creek wetlands, seven transitions occurred (Table 5; Fig. 6). At least one area that was a fully vegetated and only occasionally inundated marsh in the 1990s had transitioned to a small

pond by 2011. The cause is unclear, but this sort of transition can occur when dense accumulations of storm-rafter organic debris (wrack) is deposited on the marsh surface, killing off the vegetation underneath and

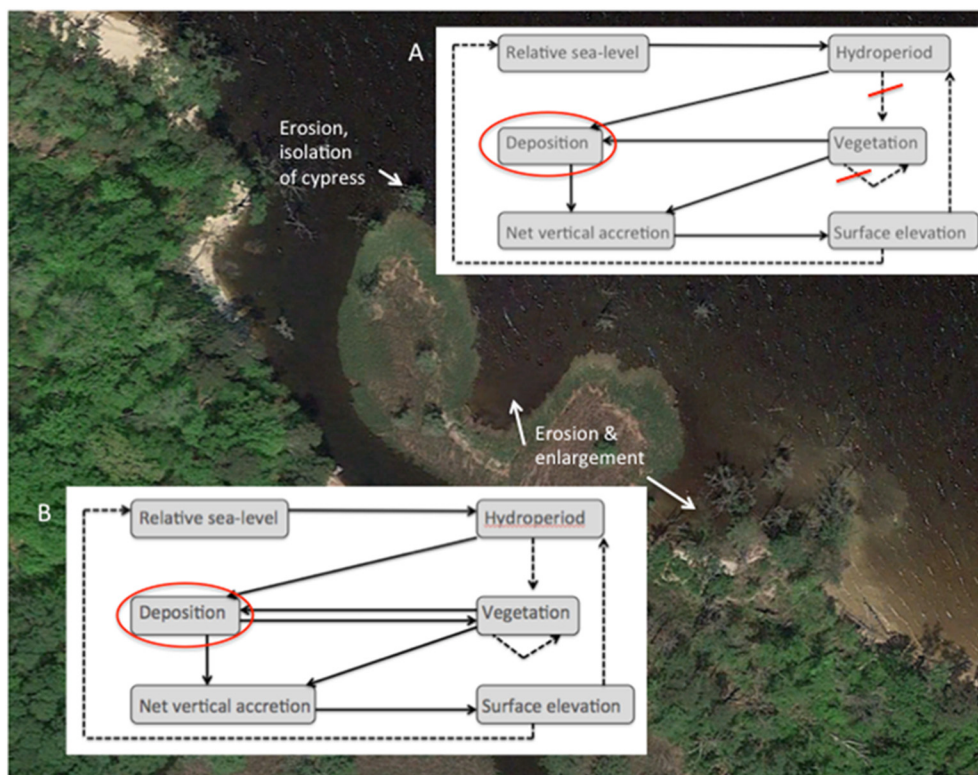


Fig. 4. Key relationships for erosion and isolation of bald cypress tree (A); and erosional enlargement of embayments (B). In (A), the hydroperiod and deposition effects on vegetation and the vegetation self-effects are irrelevant due to the ability of mature cypress to survive but not reproduce in flooded conditions. In (B), the vegetation-deposition interactions become negligibly small.

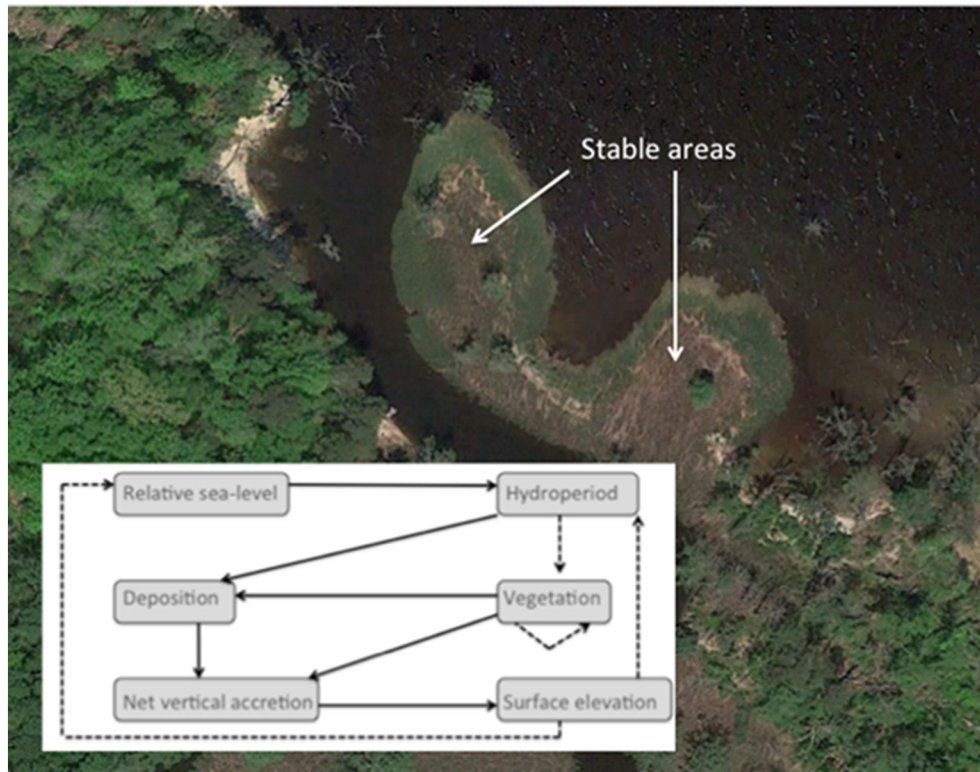


Fig. 5. In the stable areas of Otter Creek Marsh, the absence of deposition effects on vegetation produce a stable configuration.

initiating a depression. As relative sea level rises, it is not unusual for marshes to gradually encroach on adjacent uplands. This upland-to-marsh transition is occasionally visible on the imagery but more commonly indicated in the field by organic-rich marsh muck onlapping sandy, sometimes oxidized, upland soil. Fieldwork in the 1990s showed this to be pervasive along the marsh/forest ecotone, though only in a few places (such as the example marked in Fig. 6) was this evident from the aerial photographs. Conversion of open water to mudflat via sedimentation and of marsh to open water via erosion also occurred.

The peninsula separating Anderson Creek from the Neuse River is narrow at some points, and storm overwash of sand from the Neuse beaches across the peninsula into the marshes has occurred at least twice between 1990 and 2007 and in 2011 and 2015. This resulted in a marsh-to-sand ridge transition. Older such sand ridges have been stabilized, transitioning to early successional stage forested upland.

A key difference between the AC and OCM sites is that in the former wetland encroachment onto adjacent uplands occurs. This is possible because of the low elevation and relief of the latter. At OCM, by contrast, adjacent uplands are eroding bluffs or cliffs of the Neuse River. Though

the cliffs themselves are retreating, the sand beaches and mudflats at their base are too storm-exposed to allow wetland vegetation to establish. Thus, at OCM the wetland complex as a whole is unable to migrate (though upland encroachment likely occurs in wetlands farther upstream on Otter Creek).

3.4. Fragmentation

Fragmentation is indicated by the appearance of new features (sand ridges, sand beach, isolated cypress) during the study period and by the development of new landforms within existing ones (e.g., ponds within marsh). The net conversion to open water is also patchy. Fragmentation is also reflected in the complexity of the transitions.

The network of geomorphic transitions at the two sites is shown in Fig. 7. In addition to the observed changes at AC, three other changes are shown that are not directly verified within the study zone but do frequently occur in Neuse River estuary wetlands. Sand ridges can be self-reinforcing because of trapping of windblown sand by vegetation (this was observed at OCM). Conversion of mudflats to either marsh (via

Table 4
Geomorphic changes, 1990–2015, Otter Creek Mouth.

Change	Transition(s)	Change or disturbance	Key processes
Erosion, beach formation	Vegetated bluff to eroding bluff with sand beach	Tropical cyclone	Destruction, removal of vegetation; sand delivery via slope failure
NW tip erosion, cypress isolation	Swamp/marsh wetland to shallow water with isolated tree	Gradual erosion ^a	Shoreline erosion, marsh vegetation loss, persistence of cypress tree
Upward extension of marsh fringe	Upland or high marsh to <i>Juncus</i> marsh	Relative sea level rise	Increase in water table elevation & hydroperiod; vegetation dispersal
Erosion & enlargement of embayments	Marsh & swamp fringe to shallow water	Gradual ^a erosion; relative sea level rise	Shoreline erosion; marsh vegetation loss; persistence of cypress trees
Sand ridge formation	Densely vegetated upland to sparsely vegetated sand ridge	Storm sand deposition	Overwash, sand deposition, vegetation burial & establishment
Creek edge cypress establishment	Marsh fringe to isolated cypress	Cypress seed dispersal & germination; gradual ^a erosion	Tree growth; sediment trapping & substrate stabilization; marsh shore erosion

^a Occurring over multiple events.

Table 5
Geomorphic changes, 1990–2014, Anderson Creek.

Change	Transition(s)	Change or disturbance	Key processes
Pond formation	Marsh to enclosed pond	Storm	Vegetation destruction by storm-rafter debris; local erosion
Upward extension of marsh fringe	Upland to marsh/wetland	Relative sea level rise	Gradual rise of water table; increased hydroperiod; wetland vegetation expansion
Sand ridge formation	Marsh to sand ridge	Storm sand deposition	Overwash, sand deposition, vegetation burial & establishment
Sand ridge stabilization	Sand ridge to vegetated upland	Vegetation establishment	Vegetation succession; erosion protection
Mudflat formation	Open water to mudflat	Sedimentation	Local bottom sedimentation & accretion
Marsh loss	Marsh fringe to open water	Shoreline erosion	Shoreline erosion; marsh vegetation loss

vegetation establishment and sedimentation) or open water (owing to substrate erosion and water level rise) are also possible.

The simple directed graphs of Fig. 7 were converted to adjacency matrices, with entries of 1 where a transition from the column to the row component occurred and zero otherwise. The largest eigenvalue of the adjacency matrix (λ_1) is the spectral radius. This can be interpreted relative to a spectral radius for a directed graph of a one-way linear sequence of 0, or 1.0 if it is assumed that the final state is self-reinforcing. For the OCM graph, $\lambda_1 = 1.618$; and spectral radius for AC is 1.466. Both λ_1 values are less than the theoretical maximum for a system where any state can transition to any other ($N-1$ to N , where N is the number of edges or components, and depending on whether self-reinforcing links are included). However, both are considerably more complex than a simple sequential replacement. Fath (2007), who applied this type of analysis to ecological food webs represented as directed graphs, considered $\lambda_1 > 1$ to indicate a complex network.

3.5. Robustness and path stability

Results above show the geomorphic transitions at the study sites in response to SLR and storms over a 25-year period. The general model of wetland response suggests instability and nonresilience, and the observed pattern of state transitions indicates a complex network consistent with fragmentation. Path stability indicates whether a particular network pattern of changes – in this case those observed at OCM and

AC – is likely to persist in the face of changes in external forcings or boundary conditions. In this case these could include acceleration in relative SLR, biotic disturbances such as introduction of marsh-modifying fauna (e.g., nutria, muskrat) or severe fire. In other Neuse estuary wetlands a number of anthropic changes are also possible.

Based on field evidence and observed changes, the network of transitions shown in Fig. 7 were interpreted as chronosequence networks (Phillips, 2015). Rather than arrows showing observed changes from one landform or landscape element to another, as above, this approach shows links among the components in terms of whether the presence of a given landform potentially enables, or prevents, eventual transition to another (Fig. 8; Table 6). Absence of an arrow indicates no direct relationship or that the features do not occur spatially adjacent to each other. Thus, for example, the negative link from sand ridge to marsh in Fig. 8 indicates that once established, presence of this convex, higher elevation form makes establishment or reestablishment of marsh less likely. Conversely, the positive link from marsh to sand ridge exists because the marsh represents a low-relief but high roughness surface conducive to deposition of overwash sand. Positive self-links in Fig. 8 indicate the ability of some features to autogenically expand. The links shown in Fig. 8 are briefly explained in Table 5.

At OCM the largest eigenvalue is always positive ($\lambda_1 = 2$ when all values of the adjacency matrix are 0 or 1). At AC the largest eigenvalue is also positive, whether the links that are likely present but not directly observed (dotted lines in Fig. 8B) are included or not ($\lambda_1 = 1$ when all values of the adjacency matrix are 0 or 1).



Fig. 6. Geomorphic changes, Anderson Creek, 1990–2015 (base image, 2014, Google Earth™).

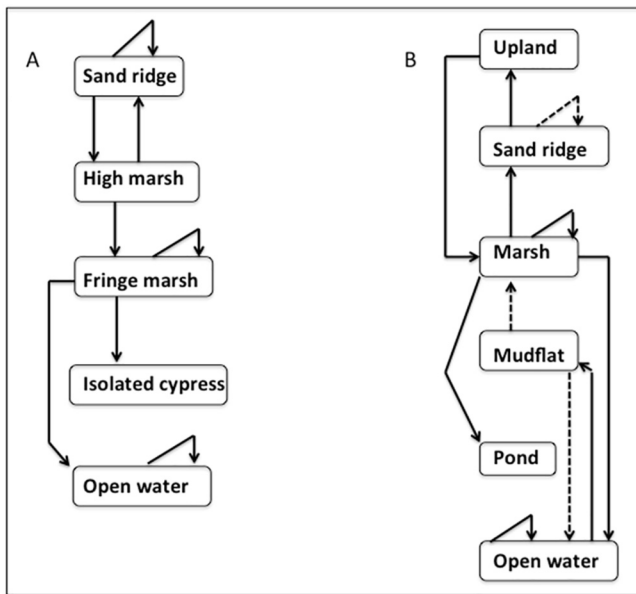


Fig. 7. Geomorphic transitions at Otter Creek Mouth (A) and Anderson Creek (B) in graph form. Dotted lines in (B) indicate phenomena not verified within the AC study area, but that have been observed in the vicinity.

A largest Lyapunov exponent (eigenvalue) of 1 indicates low divergence: unstable, divergent evolution dominated by a single sink state. This is the case for AC, with open water as the attracting state. If $\lambda_1 > 1$, this indicates a complex high divergence pattern with multiple possible pathways that is not robust to environmental changes.

4. Discussion

4.1. Stability model

The stability model is used here as an interpretive rather than a predictive model. Application to OCM or AC as a whole indicates instability

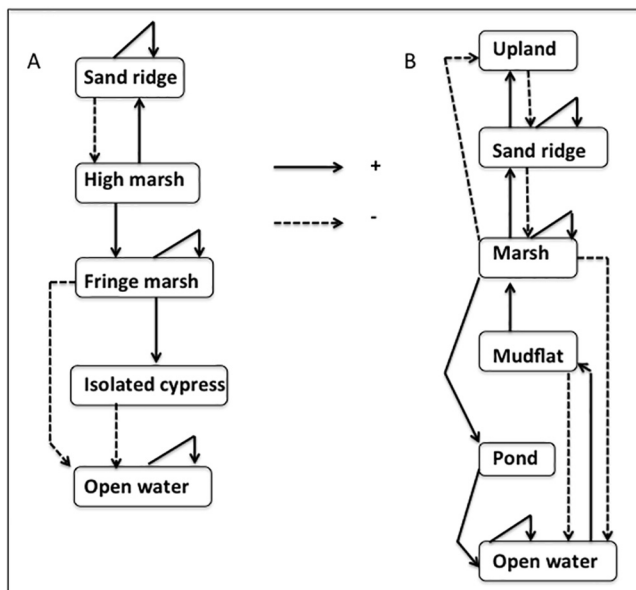


Fig. 8. Observed transitions at OCM (A) and AC (B) interpreted as chronosequences. A positive arrow indicates that presence of the feature at the arrow's origin may facilitate establishment of the feature at the end of the arrow. A negative arrow indicates that the origin feature inhibits formation of the other feature. Absence of an arrow indicates no direct relationship, or that the features do not occur spatially adjacent to each other. Positive self-effects indicate a tendency for a feature to persist once formed.

Table 6
Explanation of links (arrows) in Fig. 8.

Link	Explanation
Sand ridge self-reinforcement	Once established, vegetated ridge tends to trap additional sand
Sand ridge to high marsh	Additional elevation inhibits (re)conversion to marsh
High marsh to sand ridge	Marsh surface susceptible to storm deposition & burial of existing vegetation
High marsh to fringe marsh	High marsh susceptible to conversion because of greater inundation frequency & higher salinity
Fringe marsh self-reinforcement	Vegetation promotes sedimentation; capability to expand into high marsh
Fringe marsh to isolated cypress	Fringe marsh including cypress subject to preferential preservation of cypress as erosion & drowning occur
Fringe marsh to open water	Vegetation retards shoreline erosion; promotes deposition
Open water self-reinforcement	Wave action inhibits deposition & vegetation establishment
Upland to sand ridge	Trees not subject to burial
Sand ridge to upland	Stabilization of ridge & succession lead toward upland state
Sand ridge to marsh	Additional elevation inhibits (re)conversion to marsh
Marsh self-reinforcement	Vegetation promotes sedimentation; capability to expand into high marsh
Marsh to sand ridge	Marsh surface susceptible to storm deposition & burial of existing vegetation
Marsh to open water	Vegetation retards shoreline erosion; promotes deposition
Marsh to pond	Marsh provides wrack & potential setting for pond
Mudflat to marsh	Sedimentation & vegetation establishment may allow marsh development
Mudflat to open water	Susceptible to conversion via substrate erosion & water level rise
Pond to open water	Erosion of surrounding marsh leads to conversion

and divergent development of the wetland landscape, which is indeed occurring at the Neuse estuary study sites. Note, however, that the typical model logic can be inverted, linking observed changes in specific patches or subsections of the study sites to the model to interpret key interrelationships. This shows not only that dynamical stability and resilience varies at a very local scale within a small coastal wetland but also that the key form-process interactions determining stability also vary locally.

OCM and AC as a whole and most of their individual subenvironments are dynamically unstable and thus nonresilient in the sense that geomorphic responses to SLR will not restore, exactly or even more-or-less, what was there before. Both are also experiencing a net loss of marsh and wetland to open water and mudflats and landscape fragmentation.

While OCM, AC, and similar wetlands are capable of responding to SLR as a shifting mosaic of landforms and habitats, relative SLR is resulting in an inexorable loss of the wetlands. No net lateral accretion was observed (though this does occur locally for the emerging mudflats and marshes in AC) and the erosional embayments have steadily enlarged. Further, no opportunity exists at OCM for spatial translation onto current upland surfaces. Otter Creek near its mouth is bounded by relatively steep bluffs (relief of 7 to 10 m) associated with the dissected valley sideslope of the Neuse River, which essentially provides a barrier to upland expansion of the marsh. Adjacent Neuse River bluffs are retreating (in some cases nearby up to ~30 m since 1996, based on documented conditions prior to Hurricanes Bertha and Fran; Phillips, 1999b). However, exposure to storm waves at the bluff bases does not allow marsh establishment there.

The local geomorphic state transitions within OCM and AC are driven by storm events as well as sea level. Some of these may be major tropical or mid-latitude cyclones (tropical storms, hurricanes, and northeasters); but smaller, more frequent storm events are also relevant. Thus, the direct effects of SLR may be less important than its role in insuring that storm impacts are consistently focused at or above

and inland of the current shore zone. This is consistent with some other studies. In Denmark, Kim et al. (2011, 2013) found that effects of climate change on storm climatology were more important than SLR for marsh geomorphology. Kirwan et al. (2012) found that vegetation growth in Virginia marshes was not strongly affected by SLR. Their position in the upper intertidal zone and low relief caused the marshes to be unresponsive to sea level and more sensitive to other controls.

4.2. Geographical and historical contingency

The laws relevant to coastal wetlands and rising sea level are incorporated in the general stability model and have been in any case extensively treated elsewhere (e.g., Reed, 1990, 2002; Phillips, 1992a; French, 2006; Morris, 2006; Passeri et al., 2015). In general concurrence with earlier studies, results here indicate predominantly dynamical instability and low resilience, so that disturbance of marshes experiencing SLR is unlikely to result in a recovery to the predisturbance state and generally implying a trend toward fragmentation.

However, place and history factors cannot be ignored. While the relationships in the general stability model are widely applicable, in some situations some phenomena may not be relevant, potentially modifying the stability properties. At OCM, for instance, the interior high marsh is dynamically stable for the case of relative sea level rise. Granted, in this specific case the small area involved makes this relatively trivial, but it illustrates the fact that local environmental gradients and fine-scale topographic and edaphic variability may create local variations in stability and resilience.

The surrounding topography has long been recognized as a key variable affecting the ability of wetlands to migrate upward and inland, and this is well illustrated by contrasting OCM - where steep adjacent bluffs forestall such migration - and AC, where low-relief adjacent uplands allow migration. Another key factor is the landscape setting. The OCM is directly exposed to storm winds and waves from the open water of the Neuse River and is thereby more prone to storm-caused changes than AC, which is mostly buffered from the Neuse.

A factor common to both sites, but contrasting with some other coastal wetlands, is the fact that neither receives significant inputs of fluvial sediment. Otter and Anderson creeks are low-gradient streams with mostly forested drainage basins and correspondingly low sediment loads. Most sediment from the Piedmont-draining Neuse River is sequestered upstream of the fluvial-estuary transition zone, with little delivery to the estuary (Phillips, 1992b). Mineral sediments are thus mainly derived from redistribution within the estuary system, and the sites are therefore (unlike many other coastal wetlands) insensitive to changes in upland/inland sediment production.

Bald cypress trees are a key biogeomorphic component of the environment, particularly at OCM. Mature trees are highly resistant to erosion and drowning and can survive constant inundation, though recruitment cannot occur at drowned sites. The dense root systems (including subaerial cypress knees) also have important bioprotective functions, especially with respect to shoreline erosion. However, cypress is not salt-tolerant, and increasing salinity associated with SLR is expected to increase mortality (Bellis et al., 1976). In other settings, the traits of individual species (e.g., mangroves, saltmarsh cordgrass) are likely to be similarly important.

The human and land use context is also relevant. Both study sites are bounded mostly by undeveloped public land (Croatan National Forest; Marine Corps Air Station Cherry Point). At developed sites in the region bulkheads and other shoreline erosion protection measures and landscaping often inhibit, prevent, or reverse some of the transitions observed at OCM and AC.

As is often the case, history is intertwined with place. The Holocene and contemporary sea level rise histories (Kopp et al., 2015) in part determine the lack of fluvial sediment inputs to the study site, for example, and the economic and cultural history of eastern North Carolina led to the establishment of the national forest and the air station.

Storm events are important historical factors. Two tropical cyclones in 1996, for example, resulted in the bluff-to-beach transition at OCM, and the particular timing and sequence of these events was critical in determining the erosional response (Phillips, 1999b). The 1996 hurricanes also converted minor shoreline crenulations to enlarging embayments at OCM. The AC site is less vulnerable to storm effects, but these are responsible for the overwash-derived sand ridges at the site.

4.3. Implications

Detection of regime shifts and tipping points for coastal wetlands in response to climate and sea level changes depends on system-specific modeling and analysis, Eslami-Andergoli et al. (2015) maintained. Results of this study are consistent with their argument. The general law-based stability model is only a starting point for anticipating changes in coastal wetlands, with geographically and historically contingent factors critical to forecasting or interpreting responses. The generally unstable, divergent trends and fragmentation identified at the Neuse sites are a form of self-organized patchiness, which Eslami-Andergoli et al. (2015) identified as a possible early warning signal of a major shift.

This also indicates the importance of scale, however. The Anderson Creek area investigated is about 80 ha; the OCM site only 1.2 ha. What are the key scales or extents of spatial fragmentation with respect to broader-scale coastal responses? How can we distinguish self-organized patchiness from expected, predictable spatial variations within a coastal wetland (c.f. Brinson et al., 1995; Kirwan et al., 2012)? How do interactions and dynamics of wetland subenvironments (see, e.g., Escapa et al., 2015, on salt pans) impact overall resilience? These are open questions.

4.4. Dimensions of geomorphic resilience

Different aspects of wetland response to SLR may have different relationships to the dimensions of law, place, and history. To illustrate this, here I consider six phenomena relevant to the problem, selected to show contrasts in the relative importance of the three dimensions.

First, consider wave energy mechanics - in this case the physical laws that relate the erosive energy of waves to their physical properties, i.e., energy as a function of wave height and period. Wave energy relationships to wave height and period are universal laws. The characteristics of waves that actually form are influenced by place factors such as bathymetry and fetch, and by recent storm and wind histories, but the energy relationships are entirely law-determined.

Second is the phenomenon of inland displacement. This refers to the onlapping of upland surfaces by wetlands (or the encroachment of lower wetland units onto higher units; e.g., fringe marsh into high marsh). This is strongly dependent on place factors, especially the slope and elevation of the potential migration area. It is also highly affected by laws relevant to net vertical accretion and relative SLR. History factors, except as reflected indirectly through place characteristics and accretion and relative sea level, are of minimal importance.

Vegetation responses to variations in hydroperiod and sediment deposition are also relatively insensitive to history. They are determined at one level by general principles of tolerance, survival, and growth response relative to wetness, inundation, sediment deposition, and related edaphic factors. However, such traits vary significantly by taxa, and presence or absence of taxa is in turn closely related to local and regional place factors such as habitat suitability, propagule sources, and ecological competition. Vegetation responses are also typically nonlinear and often threshold controlled and thus closely linked to local trends and conditions. History is relatively less important in a direct sense because of the relatively rapid response time of vegetation. Over longer time scales, however, historical factors related to plant dispersal and range shifts may be significant.

Overwash and the formation of sand ridges is the fourth example. While certainly general principles related to water levels, waves, and

sediment transport are relevant, overwash is basically a historically and geographically contingent phenomenon. First, of course, overwash is episodic and storm related, and for a given storm the occurrence of overwash is influenced by timing (e.g., high or low tide) and antecedent conditions. Spatially, local topography and vegetation influence not only the occurrence of overwash but whether or not it results in formation of a sand ridge or burial of marsh.

Fifth is marsh fringe erosion. General force vs. resistance relationships that combine general laws covering the force of waves and currents and resistance controlled by place factors such as sediment and vegetation properties are the primary control. History is also a major factor, via initial conditions that influence resistance (e.g., exposed erosion scarp from a previous event).

The final example is adjacent land uses. Recognizing that some laws and generalizations of economic geography may be germane, this is primarily controlled by place factors such as topography, soils, and accessibility and by historical factors having to do with settlement patterns and economic development. The establishment of Croatan National Forest in 1933–1937 is tied to the history of U.S. National Forest development more generally, and its holdings determined largely by land availability in the early 1930s. The latter, in turn, was influenced primarily by lack of demand for wetlands and inaccessible sites (determined by place factors); and the cutover, eroded nature of the upland forests, is a legacy of land use history in North Carolina. Marine Corps Air Station Cherry Point's formation in 1941–1942 was similarly influenced by land availability and the military exigencies of World War II. The nondevelopment of the portion adjacent to Anderson Creek is an outcome of the lack of accessibility from the remainder of the base, coupled with the need for an undeveloped buffer zone around the military facilities.

These relationships are summarized graphically in Fig. 9, where each example phenomenon is shown relative to high or low influences of laws, place, and history.

5. Conclusions

Geomorphic resilience is not strictly a property of system structure and relationships described by general laws that are independent of place and time. Resilience is also controlled by local place characteristics and by historically contingent factors. This is illustrated for the case of coastal wetland response to relative sea level rise.

General laws relevant to wetland response include, e.g., relationships between wave properties and energy expenditures, force/resistance relationships relevant to marsh fringe erosion, and species-specific vegetation traits that determine plant responses to inundation, salinity, sedimentation, etc. Generally applicable interrelationships

among relative sea level, marsh surface sedimentation, vegetation production, hydroperiod, and surface elevation are dynamically unstable under most, but not all, circumstances. Low resilience results in changing landscape configurations (e.g., fragmentation) as marshes respond to sea level rise but where localized contingent factors create stable, resilient conditions.

Place factors include geologic, topographic, and hydrographic settings and biogeographic factors. For the case study wetlands in North Carolina, particularly important place factors include relative exposure to open fetches from the Neuse River, slope and relief of adjacent topography, low fluvial sediment inputs, traits of vegetation such as bald cypress, and land use and ownership. History factors particularly important for the study area operate at three different temporal scales: Quaternary sea level and coastal evolution, twentieth century land use history, and the sequence and timing of storm events.

Stability, resistance, and resilience may be considered at multiple scales. While the overall trends over the past 25 years at the OCM and AC sites are consistent with dynamical instability, low resilience, and spatial fragmentation, stability may vary at the within-site scale, in terms of resilience (or not) and the major factors controlling or influencing instability. This local-scale variability is likely common to coastal wetlands because of their geomorphic and ecological sensitivity to environmental gradients of, e.g., elevation, sediment inputs, exposure, salinity, and wetness.

One lesson for geomorphic resilience in general is that geographical and historical contingencies matter, such that broad blanket statements about resilience of particular types of landforms or landscapes are problematic. Another is that the controls over stability/resilience, and even whether they occur, is likely to vary over subenvironments within a geomorphic system.

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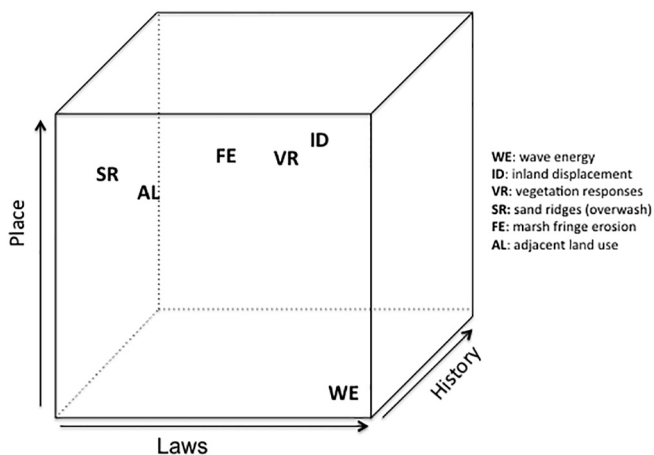


Fig. 9. Six example phenomena relevant to coastal wetland response to sea level rise (see text) according to whether they exhibit high or low influences of laws, place, and history factors.

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