An evolving research agenda for human–coastal systems

Eli D. Lazarus[a*], Michael A. Ellis[b], A. Brad Murray[c], Damon M. Hall[d]

[a]*Environmental Dynamics Lab, School of Earth & Ocean Sciences, Main Building, Park Place, Cardiff University, Cardiff, CF10 3AT, UK*

[b]*British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK*

[c]*Nicholas School of the Environment, Duke University, Durham, NC, 27708, USA*

[d]*Center for Sustainability, Saint Louis University, 3694 West Pine Mall, St. Louis, MO, 63108, USA*

*Corresponding author.
Tel: +44 029208 75563
E-mail: LazarusED@cf.ac.uk (E. D. Lazarus)

Abstract

Within the broad discourses of environmental change, sustainability science, and calls for insight into feedbacks between human activities and Earth-surface systems, a body of work has focused on the coupled economic and physical dynamics of developed shorelines. In many coastal communities, beach erosion is a natural hazard with economic costs that coastal management counters through a variety of mitigation strategies, including beach replenishment, groynes, revetments, and seawalls. As cycles of erosion and mitigation iterate, coastline change and economically driven interventions become mutually linked. Emergent dynamics of two-way economic–physical coupling is a recent research discovery. Rapid rates of change in natural coastal environments, from wetlands and deltas to inlets and dune systems, help researchers recognize, observe, and investigate couplings between non-human ecosystems and landscape-change dynamics. These fast-paced changes make developed coastal environments prime examples of observable coupling between physical processes and human activities. Having established a strong theoretical basis, research into human–coastal coupled systems has passed its early proof-of-concept phase. This paper offers three major challenges that need resolving in order to advance theoretical and empirical treatments of human–coastal systems: (1) codifying salient individual and social behaviors of decision-making in ways that capture societal actions across a range of scales (thus engaging economics, social science, and policy disciplines); (2) quantifying anthropogenic effects on alongshore and cross-shore sediment pathways and landscape evolution in coastal zones

through time, including direct measurement of cumulative changes to sediment cells resulting from coastal development and management practices (e.g., construction of buildings and dunes, bulldozer removal of overwash after major storms); and (3) reciprocal knowledge and data exchange between researchers in coastal morphodynamics and practitioners of coastal management. Future research into human–coastal systems can benefit from decades of interdisciplinary work on the complex dynamics of common-pool resources, from computational efficiency and new techniques in numerical modelling, and from the growing catalog of high-resolution geospatial data for natural and developed coastlines around the world.

Keywords: coupled systems, resource asymmetry, climate-change adaptation, hazard and risk, decision theory, environmental communication

Highlights:

- dynamics of developed coastal zones are different from those of undeveloped coastlines
- sediment shared along developed coastlines can be considered a common-pool resource
- new research agendas will need to recognize many coastlines as "human artifacts"

1. Introduction

Research recognizing humans as a geomorphic force has entered a new phase of acceleration and expansion since its early precedents (Marsh, 1869, 1882; Phillips, 1991; Hooke, 1994, 2000, 2012; Vitousek et al., 1997; Haff, 2003, 2010, 2012; Foley et al., 2005; Wilkinson, 2005; Wilkinson and McElroy, 2007; Syvitski et al., 2011; Zalaseiwicz et al., 2011; Brown et al., 2013; Ellis et al., 2013; Harden et al., 2014; Lazarus, 2014a). Physical and social insight into links and feedbacks between Earth-surface systems and human activities is a grand challenge shared across the many disciplines that study environmental change (NRC, 2001, 2002, 2010). Human activities related to agriculture, mining, and construction of physical infrastructure, from houses to highways, move more earth material than do natural geomorphic processes related to rivers, glaciers, wind, and waves (Hooke, 1994). The means by which humans redistribute soil and rock mass comprise novel sediment-transport mechanisms unto themselves (Haff, 2010, 2012). Moreover, human alterations to natural sediment-transport pathways, and the physical legacies of those alterations (McNeill and Winiwarter, 2000; Remondo et al., 2005; Neff et al., 2008; Brown et al., 2013; Dotterweich, 2013), are now well established for river systems (Criss and Shock, 2001; Syvitski et al. 2005; Walter and Merritts, 2008; Hoffman et al., 2010; Di Baldassarre et al., 2013), deltas (Syvitski et al., 2009; Xing et al., 2014), marshes and estuaries (Kirwan et al., 2011; Kirwan and Megonigal, 2013; Ma et al., 2014), and coastlines (Dolan and Lins, 1986; Nordstrom, 1994, 2000; Willis and Griggs, 2003; Long et al., 2006) around the world.

Current research in geomorphology is "employing a rapidly expanding, interdisciplinary set of tools that are revolutionizing how we understand Earth-surface processes," and benefiting from the conceptual and quantitative approaches of complexity science (Murray et al., 2009). Geomorphology is also "becoming more concerned with human social and economic values,…conservation ethics, with the human impact on environment, and with issues of social justice and equity" (Church, 2010). Exploring human and natural landscape change in an analytical context of integrated systems combines these diverse characteristics of modern geomorphology, and can reveal feedbacks and emergent phenomena that less holistic perspectives might not (Nordstrom, 1994; Haff, 2003; Werner and McNamara, 2007). In a seminal paper on the dynamics of human–landscape systems, Werner and McNamara (2007) argue that "…human–landscape coupling should be strongest where fluvial, oceanic or atmospheric processes render significant stretches of human-occupied land vulnerable to large changes and damage, and where market processes assign value to the land and drive measures to protect it from damage. These processes typically operate over the (human) medium scale of perhaps many years to decades over which landscapes become vulnerable to change and over which markets drive investment in structures, evaluate profits from those investments and respond to changes in conditions." As coastal zones worldwide are increasingly vulnerable to natural hazards (Fig. 1) (NRC, 1995, 2014; Nordstrom, 2000; Nicholls and Cazenave, 2010; Gall et al., 2011; Hoagland et al., 2012), research on coupled economic and physical dynamics of developed coastlines demonstrates the kind of insights that such an integrated systems approach can yield (Figs. 2 and 3) (McNamara and Werner, 2008a, 2008b; Slott et al., 2008, 2010; Lazarus et al., 2011b; McNamara et al., 2011; Ells and Murray, 2012; Jin et al., 2013; Murray et al., 2013; McNamara and Keeler, 2013; Williams et al., 2013, McNamara et al., 2015). For example, although coastal engineering has long grappled with the fact that local interventions against coastal erosion have updrift and downdrift consequences, recent morphodynamical work suggests the spatial and temporal scales of those distributed effects may be surprisingly large. Long-distance nonlocality can derive from not only the cumulative effects of deliberately altering sediment budgets over the long term (Fig. 4) (McNamara and Werner, 2008a, 2008b; Lazarus et al., 2011b) but also the compounding – and confounding – effects that complex coastline shapes (Coco and Murray, 2007; Murray and Ashton, 2013) can exert on shoreline behaviour through wave shadowing and net gradients in alongshore sediment flux (Fig. 5) (Slott et al., 2008, 2010; McNamara et al., 2011; Ells and Murray, 2012; Murray et al., 2013; Williams et al., 2013; Barkwith et al., 2014b).

Coastal coupled-systems research is pushing past its initial proof-of-concept phase, and in this paper we contribute to its progression in the following ways. First, we suggest that as coastal change becomes a combined function of economically driven human actions and natural physical processes (Nordstrom, 1994, 2000; Werner and McNamara, 2007; Smith et al., 2009; Gopalakrishnan et al., 2011; Lazarus et al., 2011b), developed coastlines are beginning to exemplify what economists describe as an asymmetrical commons (Ostrom et al., 1999;

Dietz et al., 2003) – an especially problematic kind of common-pool resource system in which distribution of a resource, and user access to it, is nonuniform, and the spatial boundaries that define where the system begins and ends are vague. This conceptualization of developed coastlines as coupled systems functionally integrated over large spatial and temporal scales has major implications for coastal management and the liability insurance sector (Stone and Kaufman, 1988; NRC, 2014; McNamara et al., 2015). Second, we pose three major challenges that need resolving in order to advance theoretical and empirical treatments of human–coastal systems. Thematically, these challenges involve (1) social dynamics of coastal decision-making; (2) quantifying anthropogenic effects on coastal sediment pathways; and (3) reciprocal exchange of knowledge and data between researchers and practitioners. These challenges also extend in general ways to other human–environmental systems (Liu et al., 2007; Werner and McNamara, 2007; Harden et al., 2014). We suggest possible approaches to engage each challenge. Pursuing them will require adopting or adapting strategies and lessons from perspectives and research methods formalized in other disciplines.

2. Local actions, nonlocal consequences

2.1. Common-pool resource asymmetry on developed coastlines

A groyne field that traps beach sand in front of one town tends to exacerbate erosion problems for neighbors downdrift (Pilkey and Dixon, 1996). But coastal engineering repercussions are not always so self-evident. Some systemic interdependencies may only become apparent when a major storm finds a localized weakness in hazard protection that disrupts a larger, more diffuse infrastructural network. In 2005, Hurricanes Katrina and Rita closed 21% of US refining capacity and threw national oil supply into turmoil (Yergen, 2006). In the UK, winter storms during January and February, 2014, battered down a seawall in the town of Dawlish and severed the main railway line connecting the greater southwestern peninsula of England to the rest of the country (Turner, 2014). Breaking-point events like these (Fig. 1) show why towns in the American Midwest or Atlantic-facing villages in Cornwall might have a vested interest in coastal management decisions happening in distant, seemingly unrelated towns along the Gulf of Mexico or the English Channel.

Common-pool resource systems comprise the natural phenomena, social institutions, and mechanistic links that determine how humans share open-access resources (Ostrom et al., 1999; Dietz et al., 2003). Such systems range in variety and scale from local pasture lands – the archetypal 'commons' – to the Earth's atmosphere. Already characterized by complex dynamics, some systems, especially those predicated on resources that flow or move in a prevailing direction, like a river, are further complicated by inherent asymmetry in resource distribution (Ostrom and Gardner, 1993; Dietz et al., 2003).

Irrigation systems are the classic example of an upstream–downstream asymmetrical resource (Ostrom and Gardner, 1993). Imagine a setting in which water flows from an upstream source to a downstream sink, with different farmers distributed along its route. If farmers upstream divert too much water, whether intentionally or as an unintended consequence of leaky irrigation infrastructure, then farmers downstream have access to less water. If farmers upstream keep their irrigation works in good repair, then farmers downstream benefit regardless of whether they invest in maintaining their own infrastructure. The mobility of the resource – specifically, its net transference from source to sink – means that, in the first case, farmers upstream have no obvious incentive to consider the consequences of their actions for farmers downstream; in the second case, farmers downstream have every incentive to free-ride on the investments by farmers upstream.

In coastal environments, and especially on sandy coastlines, natural perturbations or engineered alterations to the plan-view shape of the shoreline may reveal – or create – asymmetries in alongshore sediment flux. For example, seawalls, groynes, and beach replenishment are designed to contend with coastal erosion and protect valued infrastructure by arresting, countering, and altering natural sediment-transport pathways. Although coastal zones are physical systems with dynamics spanning spatial scales from meters to hundreds of kilometers, standard strategies to mitigate against coastal hazards, particularly erosion, tend to be highly localized (Pilkey and Dixon, 1996; Brown et al., 2011). These local manipulations have well known, typically asymmetrical effects on shoreline morphology updrift and downdrift, and their influences may propagate in both directions even on complex coastlines (Fig. 5). The morphological analog in rivers arises above and below dams (Petts and Gurnell, 2005). Asymmetry is not an inevitable consequence of all coastal hazard mitigation. On an approximately straight coastline segment, shoreline stabilization through beach nourishment – a soft-engineering intervention that involves importing sand from outside the local littoral system to widen a beach otherwise narrowed by persistent erosion – can have a symmetrical effect of lowering erosion rates up and downdrift. But an emergent characteristic of developed coastlines is that shoreline management decisions in one place (Fig. 2) may become an indirect function of actions elsewhere (Fig. 4) (McNamara and Werner, 2008a; Lazarus et al., 2011b; McNamara et al., 2011; Ells and Murray, 2012), such that spatial and temporal patterns in local interventions do not simply mirror natural erosion and accretion patterns in shoreline change (Williams et al., 2013; Barkwith et al., 2014a, 2014b). Much like the asymmetrical incentives and disincentives in irrigation systems, for towns located within the same littoral sediment-transport pathway, some towns may benefit for free from other towns' investments in coastal protection, or they may suffer from others' lack of investment (Williams et al., 2013).

Asymmetrical social–environmental resource systems are also typical of fisheries (Pauly et al., 2002; Dietz et al., 2003; Wilson, 2006). As with beach protection and irrigation, if the fishery involves migratory species, asymmetry is manifest in the patterns of the natural resource itself, and where small-scale and large-scale commercial fishers operate in the same territory, asymmetry is reflected in user access to the resource. On developed coastlines, this latter asymmetry arises among neighboring towns where wealth disparities mean that not all towns can invest equally in beach protection (McNamara et al., 2011; Williams et al., 2013).

Dynamics of developed coastlines therefore may be fundamentally different from those of natural, undeveloped coasts (Nordstrom, 1994, 2000; Werner and McNamara, 2007; Kelley and Brothers, 2009; Hapke et al., 2013; Lazarus, 2014b), and so require novel frameworks with which to analyze them (Ostrom, 2009). Decades of research suggests that cooperation and collaborative rule-making, among other requirements for adaptive governance, are essential for creating equitable, sustainable solutions to common-pool resource problems (Ostrom et al., 1999; Dietz et al., 2003; Ostrom 2009). However, examples of long-standing, tested, regional-scale, coordinated management decisions along developed coastlines remain rare (Kabat et al., 2005, 2009). Even when the need for integrated coastal management is clear (Stojanovic et al., 2004), the institutional structures necessary for such management may not be. In many contexts, effective management of the human–coastal environment may first require the two-fold acknowledgement that sand on developed coastlines is a shared resource (Stone and Kaufman, 1988), and that the complex coupled dynamics of developed coastal zones demand conscious efforts to ensure fair use and systemic longevity (Nordstrom, 2005). This societal context motivates opportunities for innovative coastal research.

2.2. Beach nourishment as a coupled-system exemplar

Figure 2 illustrates Werner and McNamara's (2007) description of a strongly coupled human–landscape system in terms of beach nourishment. In this generalized case, natural littoral processes (1) – alongshore and cross-shore gradients in wave-driven sediment flux – create spatial patterns of erosion and accretion. Where erosion impinges upon the infrastructure and assets that comprise a developed shoreline (2), that coastal zone becomes vulnerable to damage from hazard (3), especially where effects of cumulative erosion increase the impact of seasonal storms or an extreme event by compromising the buffer of a wide fronting beach. The typically high value of shorefront real estate, combined with the value of the beach itself as an economic asset, creates an incentive to invest in hazard mitigation and shoreline protection (4). The schematic plot in Fig. 3 represents the four parts of this same cycle in terms of their relative spatial and temporal scales. Natural littoral processes (1) drive cumulative shoreline changes over a broad range of scales; the scales over which coastal development (2) and coastal management operate are comparable. Damage events (3) are rapid by comparison, even if exacerbated by long-term, chronic erosion; large storms can affect open coasts at very large spatial scales. Individual mitigation interventions (4) – a single nourishment episode, for example – might span only part of one municipality's shorefront or might extend across several municipal jurisdictions where development is dense, but typically affect comparatively discrete segments of developed coastline at any one time.

Lazarus et al. (2011b) present a generalized, agent-based model in which a string of neighboring coastal towns situated within the same littoral cell contend individually with local beach erosion. In each town, a manager agent records the town's shoreline erosion rate and then calculates the economically optimal interval (in years) over which the town should nourish the beach. When interventions by individual towns are synchronous – effectively coordinated, even if the decision-making process itself is uncoordinated – the coupled economic–physical system settles into a stable steady-state (Fig. 4a). Each manager sees the same data, calculates the same optimal nourishment interval, and so nourishes at the same time. (In this case, each town begins with the same beach width, and the model assumes economic parity across the towns.) Most importantly, over time, each town behaves in a way that optimizes its net economic benefits – the gain brought by beach nourishment minus fixed project costs and losses incurred by not nourishing (Smith et al., 2009). By extension, the entire domain achieves its expected economic optimum. However, when the domain is subjected to a higher annual erosion rate and perturbed by one town nourishing out of phase with the rest, the synchrony destabilizes (Fig. 4b). Lateral diffusion of sand within the littoral cell results in enigmatic data series for manager agents to interpret. As they adjust and readjust their calculations of the optimal nourishment interval, the disruption travels alongshore as a propagating edge effect (Parker and Meretsky, 2004). Over time, the entire domain is affected, and never returns to a stable steady-state. Because none of the towns can achieve its maximum economic net benefit, the collective domain operates below its theoretical optimum.

Other work has extended the cycle shown in Fig. 2 to explore the effects that coastline planform can have on natural and anthropogenically manipulated sediment flux, particularly with regard to gradients in alongshore transport (Slott et al., 2008, 2010; McNamara et al., 2011; Ells and Murray, 2012; Williams et al., 2013). Figure 5, based on results from Ells and Murray (2012), shows a generalized cuspate coastline (order 10^2 km) in which a 10-km segment of the middle foreland (shown in gray) is fixed in place by a shoreline-stabilization regime of either beach nourishment (blue) or emplacement of hard structure (red). In this modeling investigation, although the largest magnitudes of shoreline change occur nearest the mitigation, significant net changes in shoreline position – tens of meters of gain and loss – manifest several tens of kilometers away (Fig. 5b). By stabilizing part of the cuspate foreland, either by supplying new sediment through periodic nourishment or by creating a sediment-starved reach dominated by hard structure, mitigation alters the gradients in alongshore sediment flux by changing the local orientation of the shoreline relative to incident waves (Fig. 5c). Wave shadowing, or filtering of the incident wave climate by the shape of the cuspate shoreline itself, imparts an additional, cumulative effect on sediment-flux gradients, with the most significant shadowing-related stabilization effects on shoreline change occurring farthest away (Fig. 5d). When the full length of the cuspate coastline is divided into different towns in a dynamic, coupled morpho-economic version of the model (McNamara et al., 2011), a town's position relative to a cape tip and the orientation of the prevailing incident wave climate can determine whether it experiences high rates of erosion despite mitigation efforts (making it a "sucker"), or whether it benefits from sand introduced to the littoral system by towns updrift and/or downdrift (making it a "free-rider") (Williams et al., 2013). Overall, secondary filtering of alongshore sediment-flux gradients by the large-scale coastal planform results in a heterogeneous spatial pattern of losers and winners, "suckers" and "free riders", distributed up and down the coastline.

These coastal studies of physical–economic coupling (e.g., Lazarus et al., 2011b; McNamara et al., 2011; Williams et al., 2013) share a common theme. When individual communities along a developed coastline stabilize their shorelines locally and independently, each affects (however unwittingly) the erosion rates that other communities are trying to mitigate – possibly even non-adjacent communities, over surprisingly long distances. Each community is therefore making local shoreline-stabilization decisions in indirect response to decisions made in other, possibly distant, communities. In such cases, the collective, emergent patterns of economic decision-making drives coastline evolution at least as much as natural forces do.

3. Major challenges – and ways forward

3.1. Understanding the dynamics of coastal decision-making

To better represent the human dynamics in models of coupled human–coastline systems, new research must engage economic, social-science, and policy disciplines to codify salient individual and social behaviors of coastal decision-making in ways that capture societal actions across a range of scales. A typical approach in assessments of coastal vulnerability – the exposure of valued infrastructure to natural hazard – is to convert socio-economic data into qualitative indices, which can raise complicated issues regarding methodological subjectivity and how to account for temporal change (Gornitz et al., 1994; McLaughlin et al., 2002). But empirical data reflecting key characteristics of social systems, including user groups and governance structures (Ostrom, 2009), can also be incorporated into representative models designed to lend transparency to system dynamics rather than to explicitly simulate a specific situation or locale. For example, common-pool resource economists have engaged a wide variety of investigatory approaches including on-location field work, focus-group workshops, game theory, and agent-based modeling (Ostrom and Gardner, 1993; Ostrom et al., 1994; Ostrom, 1999, 2007; Janssen and Ostrom, 2006) that apply equally well to developed coastlines.

Although agent-based models are already being applied to human–coastal systems, especially in the context of sandy coastlines (Werner and McNamara, 2007; McNamara and Werner, 2008a; Lazarus et al., 2011b; Williams et al., 2013; McNamara and Keeler, 2013), there is room to enhance them. For example, modeling learning behaviors in multi-agent, complex adaptive systems is a notoriously difficult problem (Axelrod, 1997; Parker et al., 2003; Panait and Luke, 2005), the crux of which lies in the modeler's rationale for how model agents function (Tesfatsion, 2003): "Should [agent] minds be viewed as logic machines with appended data filing cabinets, the traditional artificial intelligence viewpoint? Or should they instead be viewed as controllers for embodied activity as advocated by evolutionary psychologists?" Posed another way, is the purpose of a given model to represent processes that are purely logical – rule-based, and therefore effectively automatic – or processes that in fact depend on a mix of rational and irrational decisions by human participants?

A major advance for the next generation of human–landscape coastal evolution models (Murray et al., 2013) would be to incorporate agents whose behavior is economic, social, cultural, and psychological (Ostrom, 1990; Werner and McNamara, 2007), with actions that derive not only from utility theory but also from behavioral decision theory (Fischhoff, 1975; Slovic et al., 1977; Slovic, 1987; Weber and Johnson, 2009; Weber, 2010; Fischhoff, 2013). Utility theory is based on a person's preference for a given outcome, which can be calculated in various ways (von Neumann and Morgenstern, 1944). Utility functions are common in agent-based models in part because they provide a relatively straightforward way of representing rational choice and decisions that optimize net benefits over time, and because they can yield emergent, complex outcomes that are not overdetermined (Arthur, 1999; Wilson et al., 2007; Werner and McNamara, 2007; McNamara and Werner, 2008a; Lazarus et al., 2011b). By comparison, decision theory is concerned with the ways in which individuals and groups, which manifest additional complexity, make judgments based on information they interpret from their social, cultural, and physical environs. Modeling managed environments using decision-theory agents capable of accommodating ambiguity (Halpern and Kets, 2014) and innovating organizational adaptation through learning (Norman et al., 2004; Wilson et al. 2007) would be a fundamental research breakthrough, and not just for coastal science (Parker et al., 2003; Bousquet and Le Page, 2004; Wainwright and Millington, 2010).

Another goal for models of human–environmental systems should involve translating qualitative social data – for example, interviews with publics, resource users, opinion leaders, policy interveners, and system stakeholders – into coded information that guides agent behavior and results in system dynamics that can be described quantitatively. "Coding" is a core methodology of qualitative analysis (Weston et al., 2001) that involves using categorical frameworks to organize information embedded in verbal or written discourse. Methods that use empirical evidence to drive agent-based models and similarly stylized models of social dynamics are a long-standing focus of the social-science modeling community (Janssen and Ostrom, 2006). Agent behavior derived from decision-making processes and explanations articulated by people who operate in real managed environmental systems (Hall et al., 2013) might also provide a means of framing not only generalized scenarios but also spatially explicit and perhaps predictive forecasts for specific coupled systems (McNamara and Werner, 2008b). For example, real behaviors often defy modeled representations of rational agents. Translating qualitative field observations (e.g., from ethnographers and other social field analysts) into meaningful social dynamics offers opportunities for more diverse audiences to engage with fundamental research in novel ways, as work in participatory modeling, some forms of citizen science, and related transdisciplinary research efforts demonstrate (Voinov & Bosquet 2010; Voinov et al. 2010; van den Belt 2004; Nielsen & Jørgensen 2011).

3.2. Quantifying anthropogenic effects on coastal sediment pathways

New research needs to quantify anthropogenic effects on sediment pathways and coastal landscape evolution through time, with particular attention to direct measurement of cumulative changes in cross-shore sediment fluxes landward of the shoreline (with related, indirect alterations to alongshore sediment budgets) that result from coastal development and management practices. Beyond addressing how development affects coastal change over spatial and temporal scales of storm events, quantitative insight into how cross-shore fluxes change and differ as a function of development type and management strategy is needed to enable study of long-term feedbacks between coastal morphology, storm impacts, and human responses (Nordstrom, 2000). Storm events that strike low-lying, sandy reaches of coastline typically transport sand into beach-side neighborhood streets or deposit washover lobes atop roadways. Just as municipalities in northern climes have maintenance crews to remove snow after winter storms, a common post-storm practice for public-works departments in developed coastal areas is to excavate sand from streets and roadways using large earth-moving equipment. The same excavated sand may be returned to the beachfront or used to reconstruct artificial dune lines as a soft-engineering strategy for hazard defense (Dolan, 1972; Magliocca et al., 2011). Although they are not exhaustive, volumetric estimates of sand quantities used in individual, cumulative, and aggregated beach-nourishment projects (Trembanis et al., 1999; Valverde et al., 1999; Hanson et al., 2002) are still far better documented than any comparable estimates for sand volumes transported deliberately for artificial dune construction and during post-storm emergency clean-up, despite the ubiquity of these interventions (Nordstrom, 1994).

High-resolution mapping and analysis of topographic change on spatially extended reaches of coastline, along with field sedimentology, laboratory experiments, and numerical models continue to illuminate states, behaviors, and mechanisms of barrier-beach overwash (Donnelly et al., 2006; Cañizares and Irish, 2008; Houser et al., 2008; Roelvink et al., 2009; McCall et al., 2010; Priestas and Fagherazzi, 2010; Williams et al., 2009, 2012; Carruthers et al., 2013; Masselink et al., 2013; Lorenzo-Trueba and Ashton, 2014; Masselink and van Heteren, 2014; Matias et al., 2014; Durán and Moore, 2013; Lazarus and Armstrong, 2015; Shaw et al., 2015; Vinent and Moore, 2015). But observations of how patterns and quantities of overwash vary as a function of coastal development styles – how cross-shore sediment fluxes depend on the density and type of infrastructure – are needed to for improved empirical foundations supporting a generation of numerical models designed for coastal morphodynamic forecasting. Such observations could provide constraints for purely physical models of coastal morphology changes during individual storms. In addition, such observations could be synthesized into parameterizations for models that address long-term (decade to century scale) co-evolution of sandy-coastline morphology and development. Patterns and quantities of overwash, integrated over many storms, determine how the topographic shape of barrier coastlines evolves. The topographic states of barrier coastlines, in turn, determine storm impacts: higher topography (especially dunes) tends to prevent or mitigate overwash and flooding during storms. On developed coastlines, this feedback loop also involves human decision-making. If coastal development alters patterns of overwash, and therefore coastal topography, then coastal development also alters future storm impacts. Future storm impacts, aside from altering existing infrastructure, influence subsequent decisions regarding styles of coastal development and land use. Exploring how a coupled coastal–human system might respond to changing climate and socio-economic forcing requires not only improved ability to model human decision-making, but also improved ability to model the effects of human manipulations on the physical environment and sediment-transport processes.

The suggested focus here on long-term, coupled, complex feedbacks in the developed coastal system is what sets this research avenue apart from, for example, classical coastal engineering. How coastal morphodynamics research will now begin to quantify and distinguish among transient and cumulative coastline changes (List et al., 2006; Lazarus et al., 2011a) related to sediment fluxes in natural, mitigated, and coupled human–natural settings remains an open question. Reconstructions of anthropogenically altered downstream sediment fluxes have become a research focus in deltaic systems (Long et al., 2006;

Syvitski et al., 2009; Xing et al., 2014). Similarly detailed upstream–downstream, updrift–downdrift sediment budgets will become increasingly important as sediment supplies for erosion mitigation come into increased demand as a common-pool resource (McNamara et al., 2011).

3.3. Prioritizing reciprocal knowledge and data exchange

New research needs to incorporate reciprocal knowledge exchange between researchers in coastal morphodynamics and practitioners of coastal management. This mutual exchange is perhaps the most critical of the challenges described here if coastal-change research is to be worth its investment. Knowledge exchange and co-production not only grants academic researchers access to potentially critical data and a clearer understanding of socio-economic needs, but also helps coastal managers conceive of (or reconsider) what coastal research makes possible. Pivotally, without this two-way connection, research findings may never gain buy-in from decision makers, leaving even the most promising adaptation scheme no chance of advancing from concept into implementation. Coastal research aiming to be relevant at planning and management time scales – and thus connect generalized theory to specific application – needs to begin with reciprocal relationships with practitioners (Cash et al. 2003; Clark et al. 2011).

In general, robust connections between researchers and the end-user community (which can include land owners, coastal area managers, national regulators, and others) are often invoked, but in practice may amount to little more than one-way informational meetings in which academic experts deliver information to a non-academic audience with no active role in the interaction (Cash et al., 2003, 2006). The end-user coastal community always has constraints, whether budgetary or regulatory, on what can be done along their own shorefronts. They are likely to have data and information that for researchers is otherwise unknown or hard to come by in the absence of meaningful opportunities to exchange it (Collins and Evans, 2002; Ames, 2004; Martin and Hall-Arber, 2008; Lane et al, 2011). Different end-users may speculate about plans or future changes with uncertain long-term outcomes that researchers could perhaps model or test. Depending on their conception of the managed coastal system, different end-users may not realize the nonlocal consequences (in space or time or both) of particular interventions, or the role played by a physical external forcing like sea-level rise or a changing wave climate. Deliberate, cultivated reciprocity is thus a means of responsibly engaging the end-user community in a scientific research program.

Findings at intermediate stages of the research process should influence researchers' and practitioners' analytical approaches to make improvements in tandem. Research into the dynamics of developed environments ultimately must engage the people who live and work in those environments, both in order to translate their knowledge into the research for greater insight (Hall et al., 2012; Hall and Lazarus, 2015), but also to translate research insights into real societal relevance: "Once society has become a laboratory – and the citizens objects of the experiment – the door morally and politically opens to the public voice. In this situation, discovering truth becomes both public and polyvocal….The traditional technocratic concept of science has to give way to a more 'reflexive' or self-critical concept of science" (Fischer, 2000). Such "polyvocal" approaches comprise the core of sustainability science research (Cash et al., 2006; Voinov and Bousquet, 2010; Pidgeon and Fischhoff, 2011; Hall et al., 2014) and have been central to policy-relevant environmental science for decades (Jasanoff and Martello, 2004). But public participation and scientific inclusivity are not solutions unto themselves (Layzer, 2008; Haughton et al., 2015). Successful integration of local expertise relies on making knowledge commensurate across socio-cultural, bureaucratic, and scientific discourses, and then developing strategies for adapting research design to fit that context (Fischer, 2000; French et al., this issue; van Maanen et al., this issue). Processes for public participation can be designed to move beyond public outreach and toward strategic engagement capable of serving multiple uses through reciprocal knowledge exchange. Documenting, translating, mapping, and otherwise incorporating into scientific research the cumulated knowledge created and retained by individual stakeholders and networks and communities of stakeholders (Ames, 2004; St. Martin and Hall-Arber, 2008; Voinov and Bousquet, 2010) will help scientists and publics alike explain and anticipate physical and social impacts of, and responses to, coastal change.

4. Implications

Twenty years have passed since Nordstrom (1994) asserted that "human agency is not an intrusion into the coastal environment so much as it is now a part of the coastal environment and…human-altered landscapes can and should be modeled as a generic system….The direct chain of events leading from human decisions to geomorphic responses and to future changes in the coastal landscape are difficult to assess, but assessments are critical, given the inexorable transformation of the coast to a human artifact." The challenges we frame here both reassert and extend this warrant. Future research into human–coastal systems can benefit from (1) incorporating perspectives, approaches, and lessons that common-pool resource experts have been refining for decades; (2) from vast improvements in computational efficiency and numerical modeling techniques that enable new kinds of hypothetical exploration, scenario simulation, and dynamical transparency; and (3) from the growing catalog of high-resolution geospatial data for natural and developed coastlines around the world. The challenges for coastal science that we discuss hardly represent an exhaustive list. However, they align broadly with needs and interests expressed in solicitations by national funding bodies (NERC, 2013; NSF, 2014a, 2014b), and compliment initiatives related to the development of an integrated geoscience modeling infrastructure (Voinov et al., 2010; Peckham et al., 2013). We urge that strategic agendas for coastal science recognize "the inexorable transformation of the coast to a human artifact" is a real dynamic phenomenon, and that the unknowns associated with that transformation – historical and modern – are fundamental and pressing.

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References

Ames, E.P. 2004. Atlantic cod stock structure in the Gulf of Maine. Fisheries 29, 10–28.

Arthur, W.B. 1999. Complexity and the economy. Science 284, 107–109.

Axelrod, R.M. 1997. *The complexity of cooperation: Agent-based models of competition and collaboration*. Princeton University Press, Princeton, New Jersey.

Barkwith, A., Thomas, C.W., Limber, P.W., Ellis, M.A., Murray, A.B. 2014a. Coastal vulnerability of a pinned, soft-cliff coastline – part I: assessing the natural sensitivity to wave climate. Earth Surf. Dynam. 2, 295–308.

Barkwith, A., Hurst, M.D., Thomas, C.W., Ellis, M.A., Limber, P.W., Murray, A.B. 2014b. Coastal vulnerability of a pinned, soft-cliff coastline – part II: assessing the influence of sea walls on future morphology. Earth Surf. Dynam. 2, 233–242.

Brown, S., Barton, M., Nicholls, R., 2011. Coastal retreat and/or advance adjacent to defences in England and Wales. Journal of Coastal Conservation 15, 659–670.

Brown, A.G., Tooth, S., Chiverrell, R.C., Rose, J., Thomas, D.S.G., Wainwright, J., Bullard, J.E., Thorndycraft, V.R., Aalto, R. Downs, P. 2013. The Anthropocene: is there a geomorphological case?. Earth Surf. Process. Landforms. 38, 431–434. doi: 10.1002/esp.3368

Bousquet, F., Le Page, C. 2004. Multi-agent simulations and ecosystem management: a review. Ecol. Model. 176, 313–332.

Cañizares, R., Irish, J.L. 2008. Simulation of storm-induced barrier island morphodynamics and flooding. Coast. Eng. 55, 1089–1101.

Carruthers, E.A., Lane, D.P., Evans, R.L., Donnelly, J.P., Ashton, A.D. 2013. Quantifying overwash flux in barrier systems: an example from Martha's Vineyard, Massachusetts, USA. Mar. Geol. 343, 15–28.

Cash, D.W., Borck, J.C., Patt, A.G. 2006. Countering the loading-dock approach to linking science and decision making comparative analysis of El Niño/Southern Oscillation (ENSO) forecasting systems. Sci. Technol. Hum. Val. 31, 465–494.

Cash, D.W., Clark, W.C. Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., 2003. Knowledge systems for sustainable development. P. Natl. Acad. Sci. USA 100(14): 8086-8091.

Church, M. 2010. The trajectory of geomorphology. Prog. Phys. Geog. 34, 265–286.

Clar, W.C., Tomich, T.P., van Noordwijk, M., Guston, D., Catacutan, D., Dickson, N.M., McNie, E., 2011. Boundary work for sustainable development: natural resource management at the Consultative Group on International Agricultural Research (CGIAR). P. Natl. Acad. Sci. USA, published ahead of print August 15, 2011, doi:10.1073/pnas.0900231108.

Collins, H.M., Evans, R. 2002. The third wave of science studies: studies of expertise and experience. Soc. Stud. Sci. 32, 235–296.

Criss, R.E., Shock, E.L. 2001. Flood enhancement through flood control. Geology 29, 875–878.

Di Baldassarre, G., Kooy, M., Kemerink, J. S., Brandimarte, L. 2013. Towards understanding the dynamic behaviour of floodplains as human-water systems. Hydrol. Earth Syst. Sci. 17, 3235–3244.

Dietz, T., Ostrom, E., Stern, P.C. 2003. The struggle to govern the commons. Science 302, 1907–1912.

Dolan, R., 1972. Barrier dune system along the Outer Banks of North Carolina: a reappraisal. Science 176, 286–288.

Dolan, R., Hayden, B. 1981. Storms and shoreline configuration. J. Sediment. Res. 51, 737–744.

Dolan, R., Lins, H. 1986. The Outer Banks of North Carolina. U.S. Geological Survey Professional Paper, Report 1177-B, 47 p.

Donnelly, J.P., Butler, J., Roll, S., Wengren, M., Webb III, T. 2004. A backbarrier overwash record of intense storms from Brigantine, New Jersey. Mar. Geol. 210, 107–121.

Donnelly, C., Kraus, N., Larson, M. 2006. State of knowledge on measurement and modeling of coastal overwash, J. Coastal Res. 22, 965–991.

Dotterweich, M. 2013. The history of human-induced soil erosion: geomorphic legacies, early descriptions and research, and the development of soil conservation—a global synopsis. Geomorphology 201, 1–34.

Durán, O., Moore, L.J. 2013. Vegetation controls on the maximum size of coastal dunes. Proc. Nat. Acad. Sci. 110, 17217–17222.

Ellis, E.C., Kaplan, J.O., Fuller, D.Q., Vavrus, S., Goldewijk, K.K., & Verburg, P.H. 2013. Used planet: A global history. P. Natl. Acad. Sci. USA 110, 7978–7985.

Ells, K., Murray, A.B. 2012. Long-term, non-local coastline responses to local shoreline stabilization. Geophys. Res. Lett. 39, L19401.

Fischer, F. 2000. Citizens, experts, and the environment: The politics of local knowledge. Duke University Press, Durham, North Carolina.

Fischhoff, B. 1975. Hindsight is not equal to foresight: The effect of outcome knowledge on judgment under uncertainty. J. Exp. Psychol. Human. 1, 288–299.

Fischhoff, B. 2012. Risk Analysis and Human Behaviour. Earthscan, New York.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P. K. 2005. Global consequences of land use. Science 309, 570–574.

French, J.R., Payo, A., Murray, A.B., Orford, J., Elliot, M., Cowell, P. Appropriate complexity for the prediction of coastal and estuarine behavior at decadal and centennial scales. Geomorphology (this issue).

Gall, M., Borden, K.A., Emrich, C.T., Cutter, S.L. 2011. The unsustainable trend of natural hazard losses in the United States. Sustainability 3, 2157–2181.

Gornitz, V.M., Daniels, R.C., White, T.W., Birdwell, K.R. 1994. The development of a coastal risk assessment database: vulnerability to sea-level rise in the US Southeast. J. Coastal Res. 12, 327–338.

Haff, P.K. 2003. Neogeomorphology, prediction, and the Anthropic landscape. In: Wilcock, P.R., Iverson, R.M. (Eds.), Prediction in Geomorphology. AGU Monograph Series 135, 15–26.

Haff, P.K. 2010. Hillslopes, rivers, plows, and trucks: mass transport on Earth's surface by natural and technological processes. Earth Surf. Proc. Land. 35, 1157–1166.

Haff, P.K. 2012. Technology and human purpose: the problem of solids transport on the earth’s surface. Earth System Dynamics 3, 417–31.

Hall, D.M., Gilbertz, S.J., Horton, C.C., Peterson, T.R. 2012. Culture as a means to contextualize policy. *Journal of Environmental Studies and Sciences* 2, 222–233.

Hall, D.M., Gilbertz, S.J., Horton, C.C., Peterson, T.R. 2013. Integrating divergent representations of place into decision contexts. In: Stewart, W.P., Williams, D.R., Kruger, L. (Eds.), Place-based Conservation. Springer, Netherlands, 121–135.

Hall, D.M., Lazarus, E.D. 2015. Deep waters: Lessons from community meetings about offshore wind resource development in the US. Mar. Policy 57, 9–17.

Hall, D.M., Lazarus, E.D., Swannack, T.M. 2014. Strategies for communicating systems models. Environ. Modell. Softw. 55, 70–76.

Halpern, J.Y., Kets, W. 2014. A logic for reasoning about ambiguity. Artif. Intell. 209, 1–10.

Hanson, H., Brampton, A., Capobianco, M., Dette, H.H., Hamm, L., Laustrup, C., Lechuga, A., Spanhoff, R. 2002. Beach nourishment projects, practices, and objectives—a European overview. Coast. Eng. 47, 81–111.

Hapke, C.J., Kratzmann, M.G., Himmelstoss, E.A., 2013. Geomorphic and human influence on large-scale coastal change. Geomorphology 199, 160-170.

Harden, C.P., Chin, A., English, M.R., Fu, R., Galvin, K.A., Gerlak, A.K., McDowell, P.F., McNamara, D.E., Peterson, J.M., Poff, N.L., Rosa E.A., Solecki, W.D., Wohl, E.E. 2014. Understanding human–landscape interactions in the "Anthropocene". Environ. Manage. 53, 4–13.

Haughton, G., Bankoff, G., Coulthard, T.J., 2015. In search of 'lost' knowledge and outsourced expertise in flood risk management, T. I. Brit. Geogr. doi:10.1111/tran.12082.

Hoagland, P., Jin, D., Kite-Powell, H.L. 2012. The costs of beach replenishment along the U.S. Atlantic Coast. J. Coastal Res. 28, 199–204.

Hoffman, R.N., Dailey, P., Hopsch, S., Ponte, R.M., Quinn, K., Hill, E.M., Zachry, B. 2010. An estimate of increases in storm surge risk to property from sea level rise in the first half of the twenty-first century. Weather, Climate, and Society 2 271–293.

Hooke, R. LeB. 1994. On the efficacy of humans as geomorphic agents. GSA Today 4, 217, 224–225.

Hooke, R. LeB. 2000. On the history of humans as geomorphic agents. Geology 28, 843–846.

Hooke, R. LeB., Martín-Duque, J.F., Pedraza, J. (2012). Land transformation by humans: a review. GSA Today 22, 4–10.

Houser, C., Hapke, C., Hamilton, S. 2008. Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms. Geomorphology 100, 223–240.

Janssen, M.A., Ostrom, E. 2006. Empirically based, agent-based models. Ecol. Soc. 11.

Jasanoff, S., Martello, M.L. (Eds.). 2004. Earthly politics: local and global in environmental governance. MIT Press, Cambridge, Massachussets.

Jin, D., Ashton, A.D., Hoagland, P. 2013. Optimal responses to shoreline changes: an integrated economic and geological model with application to curved coasts. Nat. Resour. Model. 26, 572–604.

Kabat, P., Fresco, L.O., Stive, M.J.F., Veerman, C.P., van Alphen, J.S.V.L., Parmet, B.W.A.H., Hazeleger, W., Katsman, C.A. 2009. Dutch coasts in transition. Nat. Geosci. 2, 450–452.

Kabat, P., van Vierssen, W., Veraart, J., Vellinga, P., Aerts, J. 2005. Climate proofing the Netherlands. Nature 438, 283–284.

Kelley, J.T., Brothers, L.T. 2009. Camp Ellis, Maine: a small beach community with a big problem…its jetty. Geol. S. Am. S. 460, 1–20.

Kirwan, M.L., Megonigal, J.P. 2013. Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504, 53–60.

Kirwan M.L., Murray, A.B., Donnelly, J.P., Corbett, D.R. 2011. Rapid wetland expansion during European settlement and its implication for marsh survival under modern sediment delivery rates. Geology 39, 507–510.

Kochel, R.C., Dolan, R. 1986. The role of overwash on a mid-Atlantic coast barrier island. J. Geol. 94, 902–906.

Lane, S.N., Odoni, N., Landström, C., Whatmore, S.J., Ward, N., Bradley, S. 2011. Doing flood risk science differently: an experiment in radical scientific method. T. I. Brit. Geogr. 36, 15–36.

Layzer, J.A. 2008. Natural experiments: ecosystem-based management and the environment. MIT Press, Cambridge, Massachusetts.

Lazarus, E.D. 2014a. Land grabbing as a driver of environmental change. Area 46, 74–82.

Lazarus, E.D. 2014b. Threshold effects of hazard mitigation in coastal human–environmental systems. Earth Surf. Dynam. 2, 35–45.

Lazarus, E.D., Armstrong, S. 2015. Self-organized pattern formation in coastal barrier washover deposits. Geology, doi:10.1130/G36329.1

Lazarus, E., Ashton, A., Murray, A.B., Tebbens, S., Burroughs, S. 2011a. Cumulative versus transient shoreline change: Dependencies on temporal and spatial scale. J. Geophys. Res.-Earth, 116, F02014.

Lazarus, E. D., McNamara, D. E., Smith, M. D., Gopalakrishnan, S., Murray, A. B. 2011b. Emergent behavior in a coupled economic and coastline model for beach nourishment. Nonlinear Proc. Geoph. 18, 989–999.

List, J.H., Farris, A., Sullivan, C. 2006. Reversing storm hotspots on sandy beaches: Spatial and temporal characteristics. Mar. Geol. 226, 261–279.

Long, A.J., Waller, M.P., Plater, A.J. (2006). Coastal resilience and late Holocene tidal inlet history: the evolution of Dungeness Foreland and the Romney Marsh depositional complex (UK). Geomorphology, 82, 309–330.

Lorenzo-Trueba, J., Ashton, A.D. 2014. Rollover, drowning, and discontinuous retreat: distinct modes of barrier response to sea-level rise arising from a simple morphodynamic model. J. Geophys. Res.-Earth 119, 779–801.

Ma, Z., Melville, D.S., Liu, J., Chen, Y., Yang, H., Ren, W., Zhang, Z., Piersma, T., Li, B. 2014. Rethinking China's new great wall. Science 346, 912–914.

Magliocca, N.R., McNamara, D.E., Murray, A.B. 2011. Long-term, large-scale morphodynamic effects of artificial-dune construction along a barrier-island coastline, J. Coastal. Res. 27, 918–930.

van Maanen, B., Nicholls, R.J., Barkwith, A., Bonaldo, D., Burningham, H., French, J.R., Murray, A.B., Payo, A., Thornhill, G., Townend, I.H., van der Wegen, M., Walkden, M.J.A. Simulating mesoscale coastal evolution for decadal coastal management: a hybrid method integrating multiple, complementary modeling approaches. Geomorphology (this issue).

Marsh, G.P. 1869. Man and Nature, or Physical Geography as Modified by Human Action. C. Scribner, New York.

Marsh, G.P. 1882. The Earth as Modified by Human Action. C. Scribner, New York.

Masselink, G., Turner, I. L., Conley, D., Ruessink, G., Matias, A., Thompson, C., Castelle, B., Wolters, G. 2013. BARDEX II: Bringing the beach to the laboratory–again. J. Coastal. Res. 65, 1545–1550.

Masselink, G., van Heteren, S. 2014. Response of wave-dominated and mixed-energy barriers to storms. Mar. Geol. doi:10.1016/j.margeo.2013.11.004.

Matias, A., Blenkinsopp, C.E., & Masselink, G. 2014. Detailed investigation of overwash on a gravel barrier. Mar. Geol. 350, 27–38.

McLaughlin, S., McKenna, J., Cooper, J.A.G. 2002. Socio-economic data in coastal vulnerability indices: constraints and opportunities. J. Coastal. Res. 36, 487–497.

McNamara, D.E., Gopalakrishnan, S., Smith, M.D., Murray, A.B. 2014. Climate adaptation and policy-induced inflation of coastal property value. PLoS one, 10(3), e0121278-e0121278.

McNamara, D.E., Keeler, A. 2013. A coupled physical and economic model of the response of coastal real estate to climate risk. Nature Climate Change 3, 559–562.

McNamara, D.E., Werner, B.T. 2008a. Coupled barrier island–resort model: 1. Emergent instabilities induced by strong human-landscape interactions. J. Geophys. Res. 113, F01016, doi:10.1029/2007JF000840.

McNamara, D.E., Werner, B.T. 2008b. Coupled barrier island–resort model: 2. Tests and predictions along Ocean City and Assateague Island National Seashore, Maryland. J. Geophys. Res. 113, F01017, doi:10.1029/2007JF000841.

McNamara, D.E., Murray, A.B., Smith, M.D. 2011. Coastal sustainability depends on how economic and coastline responses to climate change affect each other. Geophys. Res. Lett. 38, L07401, doi:10.1029/2011GL047207.

McNeill, J.R., Winiwarter, V. 2004. Breaking the sod: human-kind, history, and soil. Science 304, 1627–1629.

Murray, A.B., Ashton, A.D. 2013. Instability and finite-amplitude self-organization of large-scale coastline shapes. Philos. T. R. Soc. A 371:20120363.

Murray, A.B., Gopalakrishnan, S., McNamara, D.E., Smith, M.D. 2013. Progress in coupling models of human and coastal landscape change. Computers & Geosciences 53, 30–38.

Murray, A.B., Lazarus, E., Ashton, A., Baas, A., Coco, G., Coulthard, T., Fonstad, M., Haff, P., McNamara, D., Paola, C., Pelletier, J., Reinhardt, L. 2009. Geomorphology, complexity, and the emerging science of the Earth's surface. Geomorphology 103, 496–505.

National Research Council (NRC). 1995. Beach nourishment and protection. Committee on Beach Nourishment and Protection. National Academies Press, Washington, DC.

National Research Council. 2001. Grand challenges in environmental sciences. Committee on Grand Challenges in Environmental Sciences. National Academies Press, Washington, DC.

National Research Council. 2002. The drama of the commons. Committee on the Human Dimensions of Global Change. National Academies Press, Washington, DC.

National Research Council. 2010. Landscapes on the edge: new horizons for research on Earth's surface. Committee on Challenges and Opportunities in Earth Surface Processes. National Academies Press, Washington, DC.

National Research Council. 2014. Reducing coastal risk on the East and Gulf Coasts. Committee on U.S. Army Corps of Engineers Water Resources Science, Engineering, and Planning: Coastal Risk Reduction. National Academies Press, Washington, DC.

National Science Foundation (NSF). 2014a. Coastal SEES (Science, Engineering and Education for Sustainability). Program solicitation NSF 14-502. Online: http://www.nsf.gov/pubs/2014/nsf14502/nsf14502.pdf (accessed March 2014).

National Science Foundation. 2014b. Dynamics of Coupled Natural and Human Systems (CNH). Program solicitation NSF 10-612. Online: http://www.nsf.gov/pubs/2010/nsf10612/nsf10612.pdf (accessed March 2014).

Natural Environment Research Council (NERC). 2013. The business of the environment: our strategic direction. Online: http://www.nerc.ac.uk/latest/publications/strategycorporate/strategy/the-business-of-the-environment.pdf (accessed June 2014).

Neff J.C., Ballantyne, A.P., Farmer, G.L., Mahowald, N.M., Conroy, J.L., Landry, C.C., Overpeck, J.T., Painter, T.H., Lawrence, C.R., Reynolds, R.L. 2008. Increasing eolian dust deposition in the western United States linked to human activity. Nat. Geosci. 1, 189–195.

Nicholls, R.J., Cazenave, A. 2010. Sea level rise and its impact on coastal zones. Science 328, 1517–1520.

Nielsen, S.,S., Jørgensen, S.E., 2011. Evaluation of local sustainability: The case of Samsø, DK year 2011. Technical report. Energy Academy, Strandengen.

Nordstrom, K.F. 1994. Beaches and dunes of human-altered coasts. Prog. Phys. Geog. 18, 497–516.

Nordstrom, K.F. 2000. Beaches and dunes of developed coasts, Cambridge University Press, Cambridge, UK.

Nordstrom, K. 2005. Beach nourishment and coastal habitats: research needs to improve compatibility. Restor. Ecol., 13, 215–222.

Norman, T.J., Preece, A., Chalmers, S., Jennings, N.R., Luck, M., Dang, V.D., Nguyen, T.D., Deora, V., Shao, J., Gray, W.A., Fiddian, N.J. 2004. Agent-based formation of virtual organisations. Knowl.-Based Syst. 17, 103–111.

Ostrom, E. 1990. Governing the commons: The evolution of institutions for collective action. Cambridge University Press, Cambridge, UK.

Ostrom, E. 2009. A general framework for analyzing sustainability of social–ecological systems. Science 325, 419–422.

Ostrom, E., Burger, J., Field, C.B., Norgaard, R.B., Policansky, D. 1999. Revisiting the commons: local lessons, global challenges. Science 284, 278–282.

Ostrom, E., Gardner, R. 1993. Coping with asymmetries in the commons: self-governing irrigation systems can work. J. Econ. Perspect. 7, 93–112.

Ostrom, E., Gardner, R., Walker, J. 1994. Rules, games, and common-pool resources. Univ. of Michigan Press, Ann Arbor, Michigan.

Ostrom, E., Janssen, M.A., Anderies, J.M. 2007. Going beyond panaceas. P. Natl. Acad. Sci. USA 104, 15176–15178.

Panait, L., Luke, S. 2005. Cooperative multi-agent learning: The state of the art. Auton. Agent. Multi.-Ag. 11, 387–434.

Parker, D.C., Manson, S.M., Janssen, M.A., Hoffmann, M.J., Deadman, P. 2003. Multi-agent systems for the simulation of land-use and land-cover change: a review. Ann. Assoc. Am. Geogr. 93, 314–337.

Parker, D.C., Meretsky, V. 2004. Measuring pattern outcomes in an agent-based model of edge-effect externalities using spatial metrics. Agr. Ecosyst. Environ. 101, 233–250.

Pauly, D., Christensen, V., Guénette, S., Pitcher, T.J., Sumalia, U.R., Walters, C.J., Watson, R., Zeller, D. 2002. Toward sustainability in world fisheries. Nature 418, 689–695.

Peckham, S.D., Hutton, E.W., Norris, B. 2013. A component-based approach to integrated modeling in the geosciences: The design of CSDMS. Computers & Geosciences 53, 3–12.

Petts, G.E., Gurnell, A.M. 2005. Dams and geomorphology: research progress and future directions. Geomorphology 71, 27–47.

Phillips, J. D. 1991. The human role in earth surface systems: some theoretical considerations. Geogr. Anal. 23, 316–331.

Pidgeon, N., Fischhoff, B. 2011. The role of social and decision sciences in communicating uncertain climate risks, Nature Clim. Change, 1, 35–41.

Pilkey, O.H., Dixon, K.L. 1996. The Corps and the Shore. Island Press, Washington, DC.

Priestas, A.M., Fagherazzi, S. 2010. Morphological barrier island changes and recovery of dunes after Hurricane Dennis, St. George Island, Florida. Geomorphology, 114, 614–626.

Remondo, J., Soto, J., González-Díez, A., Díaz de Terán, J.R., Cendrero, A. 2005. Human impact on geomorphic processes and hazards in mountain areas in northern Spain. Geomorphology 66, 69–84.

Roelvink, D., Reniers, A., van Dongeren, A.P., de Vries, J.V.T., McCall, R., Lescinski, J. 2009. Modelling storm impacts on beaches, dunes and barrier islands. Coast. Eng. 56, 1133–1152.

Shaw, J., You, Y., Mohrig, D., Kocurek, G. 2015. Tracking hurricane-generated storm surge with washover fan stratigraphy. Geology 43, 127–130.

Slott, J.M., Murray, A.B., Ashton, A.D. 2010. Large-scale responses of complex-shaped coastlines to local shoreline stabilization and climate change, J. Geophys. Res. Earth Surf., 115, F03033, doi:10.1029/2009JF001486.

Slott, J.M., Smith, M.D., Murray, A.B. 2008. Synergies between adjacent beach-nourishing communities in a morpho-economic coupled coastline model. Coast. Manage. 36, 374–391.

Slovic, P. (1987). Perception of risk. Science 236, 280–285.

Slovic, P., Fischhoff, B., Lichtenstein, S. 1977. Behavioral decision theory. Annu. Rev. Psychol. 28, 1–39.

Smith, M.D., Slott, J.M., McNamara, D.E., Murray, A.B. 2009. Beach nourishment as a dynamic capital accumulation problem, J. Environ. Econ. Manag. 58, 58–71.

St Martin, K., Hall-Arber, M. 2008. The missing layer: Geo-technologies, communities, and implications for marine spatial planning. Mar. Policy 32, 779–786.

Stojanovic, T., Ballinger, R.C., Lalwani, C.S. 2004. Successful integrated coastal management: measuring it with research and contributing to wise practice. Ocean Coast. Manage. 47, 273–298.

Stone, P. 2011. Stratigraphy of the Anthropocene. Philos. T. Roy. Soc. A, 1036–1055.

Stone, K., Kaufman, B. 1988. Sand rights: a legal system to protect the 'shores of the sea'. Shore and Beach 56, 7–14.

Syvitski, J.P., Vörösmarty, C.J., Kettner, A.J., Green, P. (2005). Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308, 376–380.

Syvitski, J.P., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R.J. 2009. Sinking deltas due to human activities. Nat. Geosci. 2, 681–686.

Syvitski, J.P. Kettner, A. 2011. Sediment flux and the Anthropocene. Philos. T. Roy. Soc. A 369, 957–975.

Tesfatsion, L. 2003. Agent-based computational economics: modeling economies as complex adaptive systems. Inform. Sciences 149, 262–268.

Trembanis, A.C., Pilkey, O.H., Valverde, H.R. 1999. Comparison of beach nourishment along the US Atlantic, Great Lakes, Gulf of Mexico, and New England shorelines. Coast. Manage. 27, 329–340.

Turner, L. How do you fix the Dawlish problem? BBC News (online), 7 February 2014: http://www.bbc.co.uk/news/uk-26068375 (accessed February 2014).

Valverde, H.R., Trembanis, A.C., Pilkey, O.H. 1999. Summary of beach nourishment episodes on the US east coast barrier islands. J. Coast. Res. 15, 1100–1118.

van den Belt, M. 2004. Mediated modeling: A system dynamics approach to environmental consensus building. Washington, D.C.: Island Press.

Vinent, O.D., Moore, L.J. 2014. Barrier island bistability induced by biophysical interactions. Nature Clim. Change 5, 158–162.

Vitousek, P. M., Mooney, H. A., Lubchenco, J., Melillo, J. M. 1997. Human domination of Earth's ecosystems. Science 277, 494–499.

Voinov, A., Bousquet, F. 2010. Modelling with stakeholders. Environ. Modell. Softw. 25, 1268–1281.

Voinov, A.A., DeLuca, C., Hood, R.R., Peckham, S., Sherwood, C.R., Syvitski, J.P. 2010. A community approach to earth systems modeling. Eos 91, 117–118.

von Neumann, J., Morgenstern, O. 1944. Theory of games and economic behavior. Princeton University Press, Princeton, New Jersey.

Wainwright, J., Millington, J.D. 2010. Mind, the gap in landscape-evolution modelling. Earth Surf. Proc. Land. 35, 842–855.

Walter, R.C., Merritts, D.J. 2008. Natural streams and the legacy of water-powered mills. Science 319, 299–304.

Weber, E.U. 2010. What shapes perceptions of climate change? Wiley Interdisciplinary Reviews: Climate Change 1, 332–342.

Weber, E.U., Johnson, E.J. 2009. Mindful judgment and decision making. Ann. Rev. Psychol. 60, 53–85.

Werner, B. T. McNamara, D. E. 2007. Dynamics of coupled human-landscape systems. Geomorphology 91, 393–407.

Weston, C., Gandell, T., Beauchamp, J., McAlpine, L., Wiseman, C., Beauchamp, C. 2001. Analyzing interview data: The development and evolution of a coding system. Qual. Sociol. 24, 381–400.

Wilkinson, B.H. 2005. Humans as geologic agents: A deep-time perspective. Geology 33, 161–164.

Wilkinson, B.H., McElroy, B.J. 2007. The impact of humans on continental erosion and sedimentation. Geol. Soc. Am. Bull. 119, 140–156.

Williams, J., Masselink, G., Buscombe, D., Turner, I., Matias, A., Ferreira, O., Bradbury, A., Metje, N., Coates, L., Chapman, D., Thompson, C., Albers, T. Pan, S. 2009. BARDEX (Barrier Dynamics Experiment): taking the beach into the laboratory. J. Coastal Res. 56, 158–162.

Williams, J.J., Buscombe, D., Masselink, G., Turner, I.L., Swinkels, C. 2012. Barrier Dynamics Experiment (BARDEX): aims, design and procedures. Coast. Eng. 63, 3–12.

Williams, Z.C., McNamara, D.E., Smith, M.D., Murray, A.B., Gopalakrishnan, S. 2013. Coupled economic‑coastline modeling with suckers and free riders. J. Geophys. Res.-Earth 118, 887–899.

Willis, C.M., Griggs, G.B. 2003. Reductions in fluvial sediment discharge by coastal dams in California and implications for beach sustainability. J. Geol. 111, 167–182.

Wilson, J.A. 2006. Matching social and ecological systems in complex ocean fisheries, Ecol. Soc. 11.

Wilson, J., Yan, L., Wilson, C. 2007. The precursors of governance in the Maine lobster fishery. P. Natl. Acad. Sci. USA 104, 15212–15217.

Xing, F., Kettner, A.J., Ashton, A., Giosan, L., Ibáñez, C., Kaplan, J.O. 2014. Fluvial response to climate variations and anthropogenic perturbations for the Ebro River, Spain in the last 4000 years. Sci. Total Environ. 473, 20–31.

Yergen, D. 2006. Ensuring energy security, Foreign Aff. 85, 69–82.

Zalasiewicz, J., Williams, M., Fortey, R., Smith, A., Barry, T. L., Coe, A. L., Bown, P.R., Rawson, P.F., Gale, A., Gibbard, P., Gregory, F.J., Hounslow, M.W., Kerr, A.C., Pearson, P., Knox, R., Powell, J., Waters, C., Marshall, J., Oates, M.,

Figure & Figure Caption

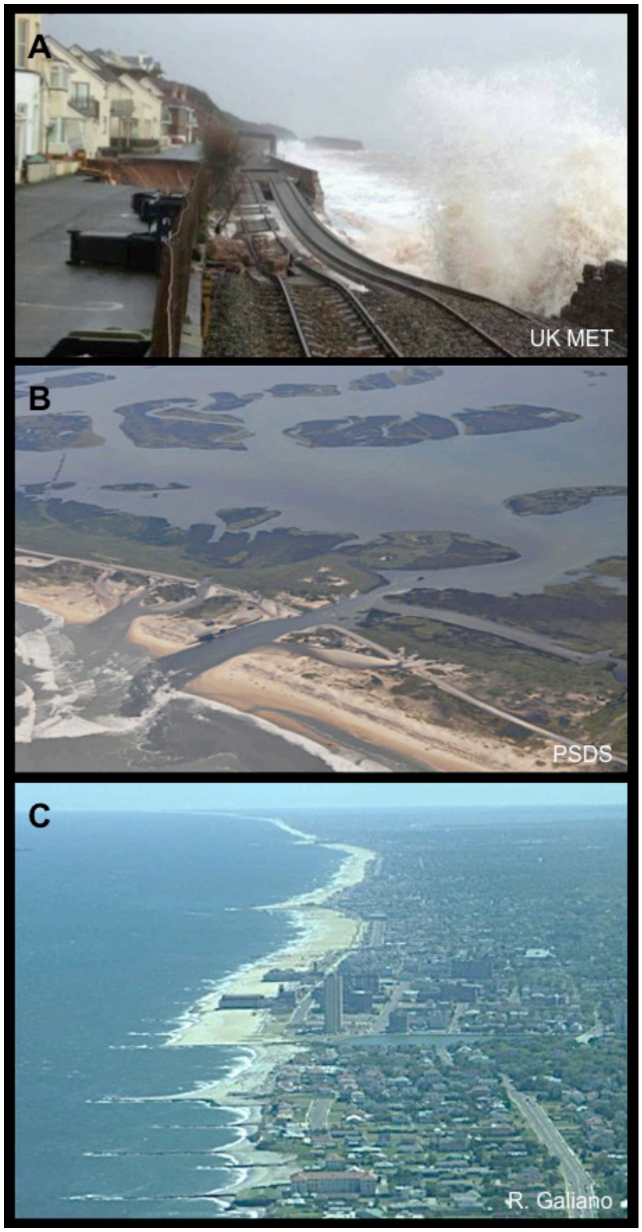

Fig. 1. (a) View east along rail line in Dawlish, UK, damaged during winter storms in February, 2014. (Photo: UK MET Office.) **(b)** Breach in Highway 12 between Duck and Rodanthe on the North Carolina Outer Banks, USA, following Hurricane Irene in August, 2011. (Photo: A. Coburn, Program for the Study of Developed Shorelines.) **(c)** View south along shoreline from Deal (foreground, no beach) to Asbury Park (middle ground, wide beach), New Jersey, USA. Prevailing direction of sediment transport in this region is from south to north. (Photo by R. Galiano.)

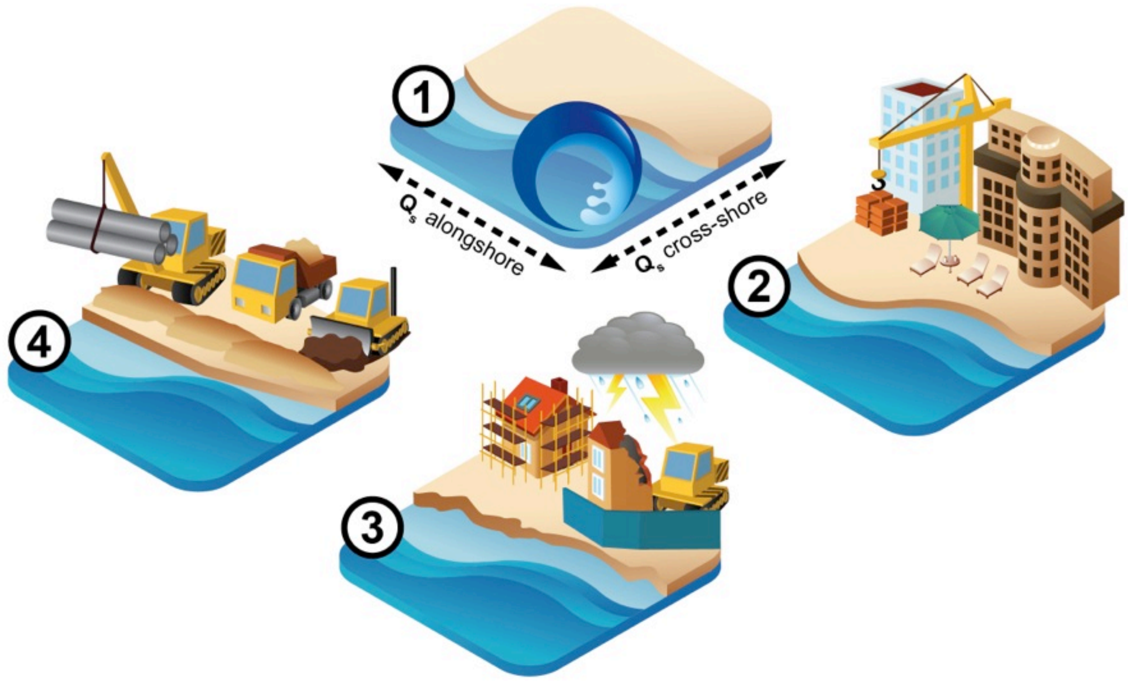

Fig. 2. Schematic of beach nourishment as a coastal exemplar of a coupled human–landscape system, following the definition by Werner and McNamara (2007): (1) natural littoral processes of alongshore and cross-shore sediment transport (Q_s) create spatial patterns of beach accretion and erosion; (2) coastal development built to benefit economically from the natural capital of a wide beach (3) becomes vulnerable to damage from coastal hazards; risk exposure (4) drives investment in hazard mitigation and shoreline protection. Where beach erosion is persistent, this cycle (1–4) repeats on a multi-annual to decadal cycle.

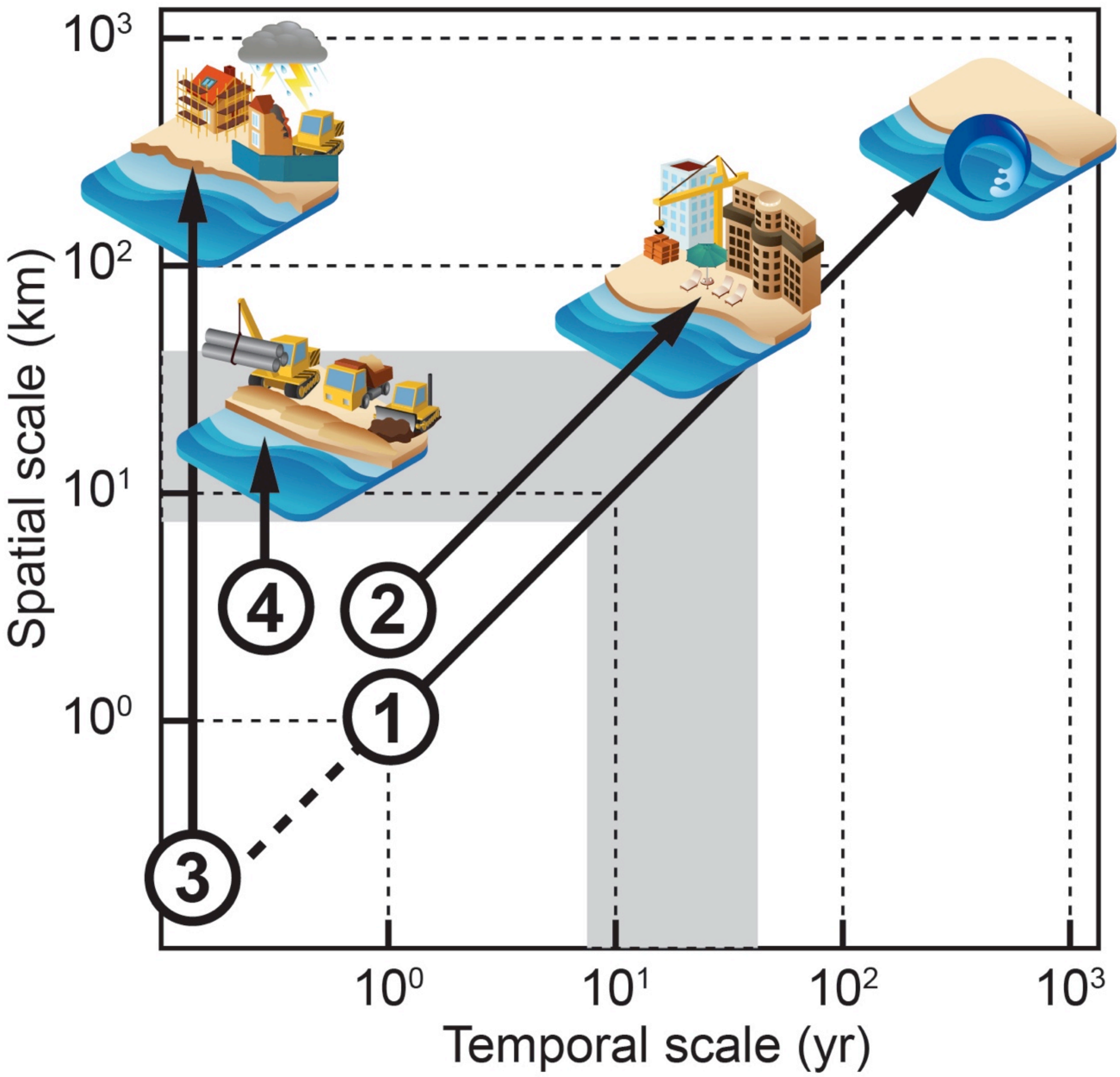

Fig. 3. Components of the beach-nourishment coupled system (Fig. 2) represented in terms of the salient spatial and temporal scales (black arrows) over which each component tends to function. Cumulative shoreline changes (1) driven by gradients in net sediment flux manifest over timescales longer than years (and spatial scales > kms), but coastal storms that cause local, rapid, significant changes during a single event (3 and dashed line) can also spur responsive mitigating actions (4). Gray box outlines the multi-annual (and mutli-km) scales over which components 1–4 overlap, as described by Werner and McNamara (2007).

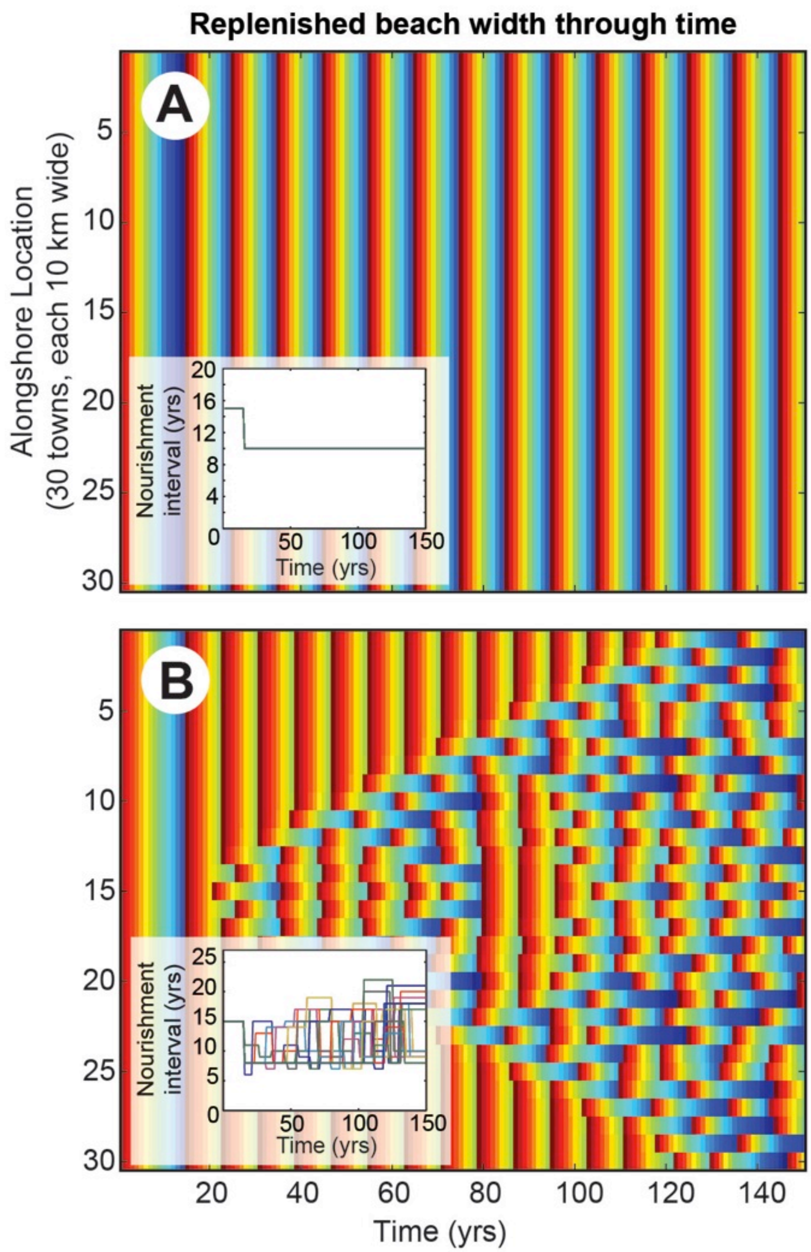

Fig. 4. Spatio-temporal series of beach width through time from the coupled physical–economic model of beach nourishment by Lazarus et al. (2011b). Hot (cool) colors represent a wide (narrow) beach. (A) When shoreline erosion rates are low and nourishment actions by all towns in the domain are coordinated, each town calculates the same optimal nourishment interval (inset) and the behavior of the coastal system is stable. (B) Under higher erosion rates and spatially uncoordinated nourishment, system behavior destabilizes such that no town settles into an economically optimal nourishment cycle (inset).

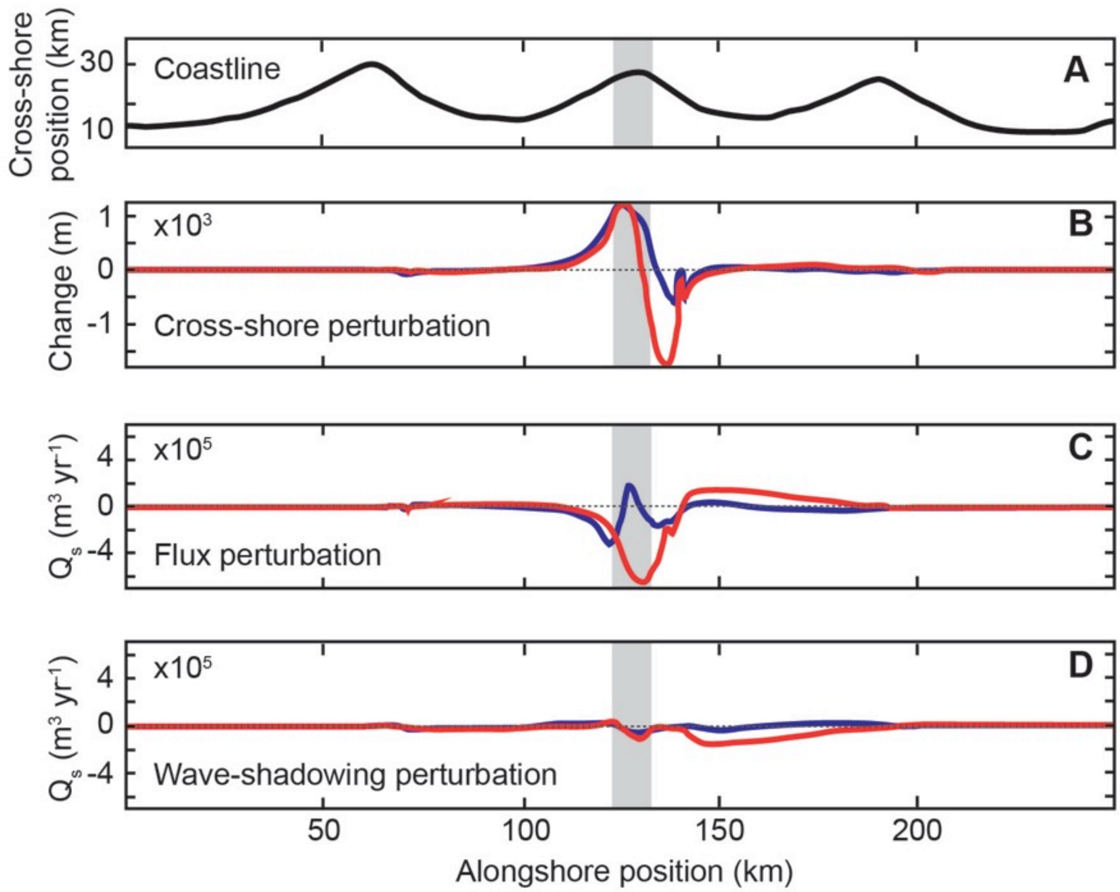

Fig. 5. Model results, reproduced from Ells and Murray (2012), of shoreline change and perturbations in alongshore sediment flux related to hard stabilization (red) and beach nourishment (blue). Here, the model is forced by a nearly symmetrical incident wave climate (with 15% more waves approaching from the upper left side of the bounding box relative to the upper right), and simulations run for 200 model years. (A) Initial model coastline defined by large-scale, self-organized capes; gray box denotes 10 km reach over which shoreline position is held fixed through time. (B) Changes in shoreline position and (C) changes in the net alongshore sediment flux, from which the shoreline adjustments derive, are highest in close proximity to the mitigation. (D) Sediment flux perturbations related to wave shadowing, a function of both the stabilization interventions and the dominant capes in the coastal planform, have strong non-local effects by comparison.