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Human–coastal coupled systems: Ten questions

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Abstract

Given the inevitability of sea-level rise, investigating processes of human-altered coastlines at the intermediate timescales of years to decades can sometimes feel like an exercise in futility. Returning to the big picture and long view of feedbacks, emergent dynamics, and wider context, here we offer 10 existential questions for research into human–coastal coupled systems.

Impact statement

On coastlines around the world, built and natural environments become systemically interconnected, or coupled, as societal decisions and natural physical processes dynamically influence each other. These "human–coastal coupled systems" express spatial and temporal patterns of change that are interesting for their mathematical properties. In theory, these properties could provide helpful context for sustainable planning and management horizons that extend over many decades. However, in the current global paradigm, the dynamics of human–coastal coupled systems are dominated by economic markets. Compared to the varied time scales of natural environmental change, markets for coastal real estate, are specifically focused on time scales of profit maximization. This article is motivated by the potential consequences of such short-sightedness, given the stark inevitabilities of future sea-level rise. Here, we sketch out possible lines of research into interconnections between built and natural coastal environments that underscore the societal importance of understanding dynamics on long-time scales.

> Due to the potential for injury from home debris, we encourage you to wear hard soled footwear on the beach…
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> – Cape Hatteras National Seashore official Twitter account, 25 May 2022

Introduction

We all know how this ends. Once the sea level is a meter or more above its current height, many human-altered low-lying coastal systems globally will manifest economic and physical configurations that are fundamentally different from their current states. Configurations will vary in local detail, but they will be changed – in expression, in behavior – from whatever they are now.

Most coastlines are human-altered coastlines: 85% of the world's coast has been significantly altered, ecologically or physically or both, by human activities (Williams et al., 2022). The dynamic coupling of human activities with natural coastal processes is focused on the intermediate timescales of years to decades. As Werner and McNamara (2007) explain:

> …[H]umans-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 (Werner and McNamara, 2007, p. 399).

Strong dynamical coupling in human–coastal systems is visible, expensive, and tends to be characteristic of populous places. Research into the human-dominated barrier systems of the USA, for example, indicates that an alternative state – undesirable relative to the status quo – is an inevitable consequence of the dynamics that have shaped those coastlines over the last several decades (Nordstrom, 1994, 2004; McNamara and Werner, 2008a, 2008b; Lazarus et al., 2011; McNamara et al., 2011; McNamara and Keeler, 2013; Williams et al., 2013; Lorenzo-Trueba and Ashton, 2014; McNamara et al., 2015; Lazarus et al., 2016; McNamara & Lazarus, 2018; Keeler et al., 2018; Lazarus and Goldstein, 2019; Lazarus, 2022a). Similarly coupled economic and physical dynamics likely extend to most market-based, temperate coastal systems around the world. So if we all know how this ends, why study these coastal coupled systems? What is important to understand about past, current and potential future land-use decisions on human-altered coastlines if their physical expressions – and underlying economic drivers – will be swamped by sea levels for which modern societies have no precedent? What is the utility of forward-looking models of these systems if – to borrow from the *Limits to Growth* canon (Meadows et al., 2004) – whatever happens on the other side of the threshold is too complex to predict, and what matters most is that there is a threshold at all? Here, we pose 10 existential questions for the study of human–coastal coupled systems, emphasizing the long-timescale context (scales beyond the intermediate timescales of strong coupling) within which the system is operating.

Questions

What emergent dynamics have resulted from strong coupling between human activities and physical processes at the coastline?

Engineered changes to a coastline impact natural processes, and in turn these altered natural processes influence future engineered changes (Werner and McNamara, 2007). Once linked, such mutual influences play out over years to decades. For example, a common form of engineered coastal change, beach nourishment, changes rates and patterns of coastal erosion, which eventually influences the timing and size of the next nourishment event. Other examples include coupling between engineered dunes or seawall construction with natural processes such as dune growth and overwash. Faster timescale processes, however – transient rip current evolution or tourists buying a round of miniature golf – are not dynamically coupled across the human/natural boundary at which the respective systems interact. Nor are long timescale processes, such as tectonically driven coastal change or political revolutions. Strong coupling and associated nonlinear interactions between human activities and coastal processes at intermediate timescales are what provide the dynamical ingredients for potential emergent behaviors. As coastal systems have only been strongly coupled in this way since the wake of the Second World War and requisite empirical records are lacking, emergent behaviors must be explored and investigated with numerical models.

McNamara and Werner (2008a, 2008b) were the first to explicitly model strong human–coastline interactions and show emergent phenomena resulting from that coupling. Emergence resulted from a destabilized response of the human-altered barrier island (relative to its natural counterpart) to impacts of a rising sea level. The instability manifested as episodic cycles of resort development and fortification, with alternate areas of collapse and (re)construction varying in both space and time. Subsequent work showed another form of emergent behavior: chaotic shoreline evolution in a model coupling economically optimized but spatially myopic nourishment cycles with alongshore sediment transport (Lazarus et al., 2011). Although the complete story arc of these emergent behaviors that play out over many decades to centuries – cyclical boom and bust in coastal real-estate, chaotic shoreline change along managed coastlines – has yet to be observed outside a numerical model (McNamara and Werner, 2008a, 2008b), we are witnessing a progression through some of the early plot points.

Other strongly coupled human–landscape systems have also shown indications of related dynamics, such as the emergent behavior associated with large and low-frequency disaster events in channelized river systems (Criss and Shock, 2001) and wildfires at the wildland–urban interface (Radeloff et al., 2018). How unique are coastal examples of disaster dynamics beyond the particulars of coastal settings, or do their dynamics translate across other systems? Are there other forms of human–landscape emergence, and when will we see them manifest – if we have not already?

What is necessary to dynamically influence the coastal system on long timescales, when the future fate of the system is forced by sea level?

Despite significant human-engineered alterations to barrier-island coastlines in time and space, there is nothing that current or near-future technology can do to change the fact that sea level will be rising for many decades to come, and in some places rising very fast – indeed, so fast that various coastal locales around the world will be inundated and perhaps cease to exist, in what collectively will constitute a catastrophic environmental and social disaster. In an irony of policy, risk reduction by hazard defense is likely exacerbating this outcome (Armstrong et al., 2016; Lazarus et al., 2018). There is a stark contradiction between current economically driven engineered practices along peopled coastlines and the long-term inevitability of a rising ocean. This contradiction is delaying necessary planning and decisions regarding how to proactively adapt to the future world of higher sea level (Keeler et al., 2018).

Improving this dire forecast will require a fundamental change in the economic system that drives short-timescale profit extraction from coastal systems (Smith et al., 2009; Gopalakrishnan et al., 2011; Gopalakrishnan et al., 2016). Extractive motive is the constant, long-timescale, goal-oriented process that has come to dynamically dominate the "global" human–coastal coupled system. A change to this long-timescale driver – one that would, for example, prioritize benefits over many generations rather than just slivers of a single one – would fundamentally weaken the currently self-reinforcing positive feedback between risk reduction and short-term market profit (Keeler et al., 2018; Lazarus et al., 2018; Lazarus, 2022b) that is distracting us from the planetary environmental drivers that really matter.

Another way to fundamentally change the long-timescale evolution of the prevailing human–coastal coupled system driven by short-term profit considerations would be to promote relational interactions among systemic variables. Relational interactions stand in direct contrast to extractive interactions. For example, having humans promote justice (Kimmerer, 2013) for a sand dune or beachscape in the same manner one would a person (Stokstad, 2022): that is, legally acknowledging intrinsic value (Nordstrom, 1990) and affording landscapes some rights (e.g., Kolbert, 2022) would be one way to create – or restore – a relational dynamic between human and natural entities. This is hardly farcical: consider surfers or coastal bird watchers who have done their part to fight for the sustained existence of surf spots and nesting areas in tidal flats – or, for that matter, Indigenous cultures whose practices of environmental sustainability succeeded for centuries to millennia.

Why do events that should warn us about the future and offer a chance to reset lead to decisions that increase systemic fragility?

Relatively regular events such as coastal storms, hurricanes, sea level anomalies, and high-tide or sunny-day flooding cause destruction of the built environment or interrupt its typical functioning. If

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we know that events cause disruption and that the frequency of disruption might increase, then why do these events not function as canaries in a coalmine? Paradoxically, destruction along human-altered coastlines often leads to a doubling-down on the built environment – increased rebuilding – that in turn leads to more money, more homes, and more lives impacted by subsequent storms. An example comes from the intensity of the built environment, quantified by building footprint size, along the US Atlantic and Gulf coasts (Lazarus et al., 2018). Destructive hurricanes ultimately result in buildings that are larger than they were before the hurricane, a phenomena that we – and others (e.g., Godschalk et al., 1989) – have heard referred to anecdotally as “storm destruction leads to urban renewal.” This phenomenon – to Build Back Bigger – is likely related to Burby’s (2006) “safe development paradox” and White’s (1945) “levee effect,” where measures meant to mitigate risk from natural hazards tend to backfire and promote further development, and in coastal settings can be observed with respect to beach nourishment (Armstrong et al., 2016). Individual buildings or subsets of larger communities may be rebuilt on elevated pilings or with wind-resistant roofs (Highfield et al., 2014) – engineering adaptations intended to reduce short-term fragility – but the longer-term, cumulative, emergent dynamic is one of exacerbated exposure and greater systemic fragility to future hazard.

Whether all of these paradoxes and effects can be neatly collapsed into a single unifying frame remains to be seen. We can think of several hypotheses as to *why* this increased fragility occurs: in all cases, there is still money to be made (e.g., McNamara and Keeler, 2013); there is a threshold in terms of event frequency that has not been crossed or a misconception of true risk (Turner and Landry, 2022); the suppression of actuarially fair insurance uptake because of disaster assistance expectations (Landry et al., 2021); risk tolerance of residents can vary, or a resident’s benefit of living in a place outweighs the risk; migration is complex or not an option (because of reasons that are financial, emotional and/or social); there are emotional and/or cultural reasons to remain (i.e., place attachment; Costas et al., 2015); the current cultural memory, or perhaps market memory, of past events (Hallstrom and Smith, 2005) is not long. More work could be done to examine systemic fragility along the coastline, explore whether other systems beyond coastal examples express similar dynamics, and investigate the root causes of these dynamics. These issues can also be explored from a climate justice lens (e.g., Hino and Nance, 2021). Answering these questions would likely inform coastline prediction, help us better understand human–coastal coupled systems, and could yield usable information for policy interventions.

How can we best test our ideas and models (numerical, conceptual) beyond the weak “test” of confirming that models match reality?

Models of human–coastal systems often require evaluation to determine if their results are able to offer useful explanations of observed phenomena. Evaluation typically takes the form of confirmation: authors display real-world and model results side by side and discuss the match (qualitatively and quantitatively) using past system states. Note that many coastal models are often developed to understand the future dynamics that could occur under certain sets of possible conditions. A useful exercise might be to develop a platform where future predictions can be tested – either for an entire domain or for key sets of variables. Coastal models could be deployed online so that future scientists could monitor the results in real-time. Just as NOAA provides both tide gauge data and tide predictions and therefore allows anyone to observe, in real-time, the match or mismatch. Similar work has also occurred in the climate modeling community focused on assessing past model predictions (e.g., Rahmstorf et al., 2012; Hausfather et al., 2020). We anticipate that observing how coastal models perform in prediction, and also analyzing in what conditions they fail, would be instructive. Model failure often points to missing processes, missing linkages, or other insights. Displaying real-time predictions is of course fraught: it would need to be clear to users and observers that these are not operational tools for forecasting. But such a service would likely be very useful to future researchers and would be worth any bruising to modelers’ egos. Adjusting our conception of model testing to include the idea of online, continuously running models, where anyone can observe model strengths and weaknesses, could be a worthwhile cultural sea-change for coastal science.

In addition to observing predictions from grid-based models, effort could be invested in determining and tracking a reduced set of emergent variables. The now classic example of this idea from geomorphology is the bedform models of Werner and Kocurek (1997, 1999), where bedform dynamics is understood in the context of pattern defects and crestline orientation. It remains unclear how and if coastal models can be distilled to a reduced set of emergent variables. A set of emergent variables could be predicted and tracked through time, plotting them on relevant phase spaces, and then try to observe if trajectories on the phase space match modeled behavior. Furthermore, the observed trajectories of emergent variables could be used to understand the dynamics of the system (i.e., Cristelli et al., 2015).

What does instability in human–coastal coupled systems look like, and how do we know when the system is unstable?

Sea level will be so high at some future date that many human–coastal systems will be forced to change significantly relative to their current state, and may drive many coastal communities to collapse. Will we know how close to collapse we are? The critical slowing down (CSD) interpretation of impending drastic system change, and its related analytic tool set for detecting early warning signals in empirical data, have been applied to a wide variety of dynamical systems with a mix of success (Wang et al., 2012; van de Leemput et al., 2014) and failure (Boettiger and Hastings, 2012; Wagner and Eisenman, 2015). Unfortunately, CSD tools can be overextended beyond their mechanistic utility. Unless the system of interest has a long-term steady state that is a fixed point – more specifically, a system in which all observed variability is imposed externally – then using CSD is akin to diagnosing acute anxiety with a thermometer. If some observed variability arises from intrinsic, internal dynamics, as is characteristic of coupled systems, then CSD tools may not illuminate any early warnings of critical instability. In our context, strongly coupled human–coastal systems are unlikely to be amenable to CSD probes.

So what are some of the symptoms we might expect to observe as human–coastal coupled systems head toward drastic change? And how do we see them in observed data? These systems contain a tangle of nonlinear interactions between human and natural processes, yet of the many complex ways these systems interact their steady state is one that is a small subset of their theoretically possible configurations. To invoke the formal terminology of dynamical systems: human–coastal coupled systems exist in attractors. Some characteristic features of this attractor state are dense populations, significant investment in erosion mitigation, immobile infrastructure, and high property values. For any system to find itself in a steady state attractor there must be dissipative processes acting. Dissipation is an umbrella term for dynamics that reduce

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differences in system states, which is how a system can find itself in a subset of its possible states (Nicolis and Nicolis, 1995). If an external perturbation kicks the system away from the attractor, the dissipative processes drive it back. As a stable systemic configuration becomes less stable, a symptom of that change is that dissipation will reduce. There are ways to measure the loss of dissipation (Williams and McNamara, 2021), but they have yet to be applied to empirical observations from coastal systems – human-altered or natural. Measurement of observed dynamical instability in coastal systems is an intriguing challenge. As dissipation in human–coastal coupled systems is reduced, a qualitative symptom that a system is spending more time outside its attractor might include, for example, cycles of destruction and repair, even during otherwise modest storm events – as occurs along low-lying road networks on reaches of the North Carolina Outer Banks.

What are the dynamical differences between current human practices along coastlines and how humans interacted with coastlines in the distant past?

The key word here is *dynamical.* Fluvial and tidal meanders were long perceived as fundamentally different physical phenomena, but viewed through the right scaling lens their dynamics reflect strong geometric and kinematic similarities (Finotello et al., 2018). Ancient and pre-modern coastlines of course differed from present-day coastlines in material and societal ways. We are not advocating direct comparisons of practices – a relative accounting of populations and infrastructural footprints and feats of engineering. Rather, what insights into systemic stability and resilience might emerge from Indigenous histories of coastal settings, from coastal and marine archeology, from palaeontological analysis of environmental change over several millennia? (And who will benefit from these insights, and how? What measures will ensure that this knowledge regarding past human coastal alterations, particularly where it derives from Indigenous sources, is not a process of further resource extraction?)

If assumptions of the scientific mainstream get dismantled slowly, slowly, then all at once (Kuhn, 1962), then coastal science has its own spaces to watch. One is Indigenous fisheries. For example, oyster shell middens are physical relics of socially complex, ecologically intensive fisheries that persisted for millennia (Reeder-Myers et al., 2022). Embedded in their strata, the geographies of their spatial distribution, and in wider contextual evidence related to middens are dynamical signatures indicative of a stable, strong attractor for this social–ecological coupled system: so what were the system states, behaviors, and dynamics that sustained such stability? As conventional management approaches to fisheries management have struggled to deliver long-term sustainability in fisheries stocks (Wilson et al., 1994; Acheson, 2006; Wilson, 2006) – or, for some species, failed to prevent ecological disaster (Berkes et al., 2006) – there is growing interest in understanding, adopting, and adapting the structures of alternative, apparently long-lived systems. If and how these alternative systems that appear to foster ecological resilience become embedded in or replace conventional fisheries practices remains to be seen – but the apparent shift in discourse toward social–ecological dynamical stability over long timescales is itself an interesting development.

Another space is in the deliberate human alteration of coastal environments, for which archeological analyses keep winding back the clock. The oldest known seawall, dated to 7,500–7,000 before present, sits on the Carmel Coast of Israel, and reflects “the extensive effort invested by the Neolithic villagers in its conception, organization and construction.” However, the authors remark, “this distinct social action and display of resilience proved a temporary solution and ultimately the village was inundated and abandoned” (Galili et al., 2019, p. 1). The abandoned city of Nan Madol, a UNESCO World Heritage Site in the Federated States of Micronesia, includes a high-walled complex of nearly 100 artificial islands and canal system built atop a coral reef flat (McCoy et al., 2016; Comer et al., 2019). Nan Madol was a dynastic seat for several hundred years, into the 17th century; the technological means by which the complex was constructed remains unresolved (Pala, 2009). Elsewhere, new insights are emerging regarding Māori settlement of Aeotearoa (New Zealand), suggesting rapid responses among the Māori to shifts in environmental conditions (Bunbury et al., 2022). Ancient and historical cultural sites are a helpful reminder that human–coastal coupled systems have emerged (and been abandoned) before, with dynamics that may parallel or diverge from modern systems in ways we cannot know if we do not ask.

How will we address the chronic, latent, cumulative problem that even minor destruction along developed coastlines causes significant environmental pollution?

The epigraph Tweet from the official account of the Cape Hatteras National Seashore refers to an event in May 2022, widely shared on social media and picked up by international news outlets, in which two unoccupied beachfront houses in Rodanthe, on the Outer Banks of North Carolina, USA, collapsed and broke apart during a day of heavy but not atypical surf conditions. Another house in Rodanthe had collapsed in February. In both cases, hazardous debris was soon bobbing around hundreds of meters offshore, and washing up on beaches over 20 km away. (Crist, 2022; Fausset, 2022; Gleeson, 2022; NPS, 2022a, 2022b; Price, 2022). In statements released by the National Park Service, the public was both warned of the hazard posed by the debris field and “invited to help clean up” (NPS, 2022a, 2022b).

These particular houses are only the most recent in a long list of such collapses, and they are hardly unique to the private-property peccadillos of the US barrier coast. When the fragility of market-driven human–coastal coupled systems (see Question “Why do events that should warn us about the future and offer a chance to reset lead to decisions that increase systemic fragility?”) results in their eventual failure, that failure will manifest in part as the abandonment of built infrastructure. An inevitable consequence of abandonment, therefore, is pollution. To clear an abandoned built environment – not a building, but a town, a city – and *not* replace it with new infrastructure is laughably cost-prohibitive (certainly over politically delicate timescales). That means whatever we see now in the coastal zone will still be there, left to get torn apart by decades of storms: beach houses, with garages full of solvents and paint and weedkiller and septic tanks somewhere under the sand; motel units and hotel blocks and strip malls and box stores; roadbeds and utility wires and storm drainage and everything else constructed that people live in and among (Weisman, 2007). This manifestation of coastal pollution – one derived directly from patterns of market-driven real-estate development on low-lying coastal floodplains – is distinguished from, but not unrelated to, more conventional and ubiquitous forms of coastal pollution, including agricultural runoff, sewage discharge, and the exposure of waste-storage landfill sites deliberately sited in areas prone to coastal erosion (Rabalais et al., 2010; Nicholls et al., 2021; Tuholske et al., 2021).

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Much of the medieval town of Dunwich, England – "Britain's Atlantis" on the eastern of England – sits in the nearshore: a dramatic example, albeit from the 13th century, of coastal abandonment following a series of major storm impacts and repeated disruptions to trade infrastructure (Sear et al., 2011, 2013; Enfield, 2022). In the past 900 years, more than 300 coastal settlements in the North Sea basin have been abandoned as a result of coastal flooding and erosion (Sear et al., 2013). What can we discern and learn about modern human–coastal coupled systems from reconstructing dynamics of abandonment, and the environmental artifacts and evidentiary legacies that remain? And what might reconstructing dynamics of settlement and abandonment teach us about possible future environmental impacts of human–coastal coupled systems?

What externalities exist beyond directly linked interactions between human and natural processes at a given location?

Numerical modeling experiments have suggested complex dynamics arising between neighboring beach towns that nourish out of sync (Williams et al., 2013; Gopalakrishnan et al., 2017). The experiments essentially demonstrated that a town could get caught out relative to its neighbors, nourishing more frequently, and therefore at greater expense, while its neighbors benefitted from lateral diffusion of nourishment sand for which they did not have to pay: a dynamic of "suckers" (the frequent nourishers) and "free-riders" (the lucky neighbors) (Williams et al., 2013). An earlier deliberately simplified numerical model of spatially extended nourishment dynamics showed that unless every town alongshore nourished simultaneously, then the system devolved into chaotic patterns of nourishment, such that no town could optimize net benefits from nourishment over time (Lazarus et al., 2011). Another numerical modeling exercise explored the possibility that some towns will be forced by their relative spatial geography to nourish more frequently than others, widening disparities in the sustainability and precarity of towns that can afford to nourish and those that cannot (McNamara et al., 2011).

On a planetary scale, these are all relatively local externalities – and they are all economic. Other local externalities are ecological, such as the largely unknown consequences of long-term, repeated beach nourishment on beach and nearshore marine ecology (Peterson and Bishop, 2005). But still other externalities are both more diffuse and ensnaring. The economic sector arguably driving archetypal human–coastal coupled system dynamics is tourism, which has two troubling consequences. One is the emergence of a "gilded trap," in which a single economic sector becomes so lucrative that it displaces all others (Steneck et al., 2011; Lazarus, 2017), resulting in a highly precarious local dependence on a market increasingly exposed to disruptive shock – whether geophysical, such as a natural hazard event, or economic, such as the effectively instantaneous cessation of tourism triggered by the COVID-19 pandemic (Lazarus, 2022b). Another consequence is the homogenization of the "beach town" – characteristics of the specific location may vary, but the provision of local amenities is largely the same around the world: hotels, condos, restaurants, beach chairs and umbrellas for hire. If all beach towns are essentially alike – and if tourist consumers *expect* them to be essentially alike – then all beach towns are similarly vulnerable to the same dynamical traps: positive feedbacks that drive negative social and/or socio-economic consequences that themselves reinforce the trapping feedback, making the trap difficult to disrupt (Lazarus, 2022b). These patterns raise the question of how human–coastal coupled systems are both driven by, and manifestations of, the infrastructure of global value chains (Tsing, 2004; Gereffi, 2018) – and what that relationship to globalization means for the evolution of human–coastal coupled system dynamics.

How do technological changes impact human–coastal coupled systems?

Coastal infrastructure is an ancient technological phenomenon (Gillis, 2015), but like many symptoms of the Anthropocene, the scale and rate of its present proliferation are unprecedented. The extent of shoreline hardening globally is unknown, but Gittman et al. (2016) estimate that in the USA, seawalls, breakwaters, and other hard structures have replaced more than half of all natural shorelines. In a forward-looking global analysis, Floerl et al. (2021) predict a 50–76% expansion of coastal infrastructure within the next 25 years, particularly in the vicinity of coastal urban centers. Bugnot et al. (2021) likewise project a 23% increase in the physical footprint of coastal and marine built structures between 2018 and 2028. These assessments reinforce what Nordstrom (1994, 2004), in synthesizing observations of human-altered coastal geomorphology from around the world, saw as the "inexorable transformation of the coast to a human artifact" (Nordstrom, 1994, p. 510).

The escalating economic costs (to say nothing of environmental costs) associated with current methods of coastal defenses (Temmerman et al., 2013) – which are there to protect coastal built environments from systemic disruption – are reminiscent of the "cycles of innovation" problem in sustainability science, as described by West (2017). "To sustain open-ended growth in light of resource limitation" and avoid systemic collapse, West explains, "requires continuous cycles of paradigm-shifting innovations" (West, 2017, p. 416). However, because open-ended growth in human and technological systems is nonlinear – indeed, super-exponential – "the time between successive innovations has to get shorter and shorter. Thus paradigm-shifting discoveries, adaptations, and innovations must occur at an increasingly accelerated pace" (West, 2017, p. 418).

In the approximately seven millennia since the advent of the seawall (Galili et al., 2019), the fundamental innovation in engineered coastal protection must be beach nourishment (NRC, 1995) and its variations, such as sediment bypassing by pumping (Castelle et al., 2009) and meganourishment (Stive et al., 2013). But beach nourishment – the deliberate replacement of sand from a nonlocal source to mitigate chronic shoreline erosion – is energy-intensive, and sea-level rise will drive up the requisite volumes of nourishment deliveries even where sand is abundant (de Schipper et al., 2021). The further irony of current modes of coastal protection, hard and soft, is that the emissions produced in their creation are contributing to the environmental forcing they are intended to counteract. While the next technological innovation in human–coastal coupled systems is unknown and unknowable in detail, the trajectory of technological innovation may be predictable (Haff, 2014). At present, that trajectory appears to be describing an ever-increasing rate of consumption (of physical space, of materials for hazard protection) that demands provisioning – but the technological limits of the system cannot keep pace. In the coming decades, will we witness a finite time singularity in human–coastal coupled systems – that is, when nonlinearly increasing demand for a resource becomes infinite within a finite period of time (Johansen and Sornette, 2001; West, 2017)? And in the absence of a technological innovation, will we witness a bifurcation in human–natural coastal systems: the aggressive preservation of some, but the abandonment of many?

Will knowing more about the dynamics of human–coastal coupled systems at intermediate timescales change the seemingly inevitable future?

How much carbon dioxide will be in the atmosphere over the course of the coming century is difficult to predict because that quantity depends on how human activities, energy technologies, and energy markets will evolve in that timeframe. Sea-level rise, however, has been set in motion – and there is no emissions scenario in which sea level will not force some low-lying human–coastal systems into a different kind of existence (Nicholls and Cazenave, 2010; Wong et al., 2014; Pörtner et al., 2019). Research into dynamics that may play out as communities and societies converge on this critical instability often alludes to potential policy implications. The Netherlands arguably leads the world in integrated, solutions-oriented considerations of human–coastal coupled systems under climate change (Kabat et al., 2005; Kwadijk et al., 2010). Their national policies for "climate-proofing" do not decouple them from the kinds of dynamics we have discussed here – but by engineering to 10,000-year timescales, they have gained themselves more time than most to problem-solve.

Some sense of what might be required for broader policy action to take long-term system collapse into account might be found in fisheries – another strongly coupled human–natural system (Ostrom, 2009). For large-scale fishing activity subject to market pressures – so, neglecting small-scale locally governed fisheries with minimal record-keeping – not until fish stocks started to decline did policies get enacted to address the possibility of collapse (Smith and Wilen, 2002). This did not prevent some fisheries from collapsing – the North Atlantic cod fishery, most famously – but catch-limit policies were nevertheless a revelation compared to the predominant attitude of the early 20th century that the ocean contained a limitless supply of fish (Smith and Wilen, 2002). Transposing this onto human–coastal coupled systems suggests that a direct, problematic signal of instability may be needed to trigger enforceable, actionable policy changes. That signal may need to be as unmistakable as water ponding in coastal streets frequently enough to disrupt profit dynamics.

Markets may begin to signal looming trouble before policy has such a reckoning (McNamara and Keeler, 2013). For example, it could be that as amenity value is lost with the encroaching sea or as insurance rates increase, coastal property values will fall. Once this happens and the tax base decreases, a Pandora's box of infrastructure adaptation problems – all of them expensive – will be without a lid. Scattered communities – and countries – will see this eventuality sooner than others, long before policies are in place to address the circumstances. Echoing fisheries, this will probably be too late to save whichever locale is unwittingly the cod equivalent. However, the possibility remains that policy actions will yet be able to prevent the collapse of many, many coastal communities worldwide (Mach and Siders, 2021) – and perhaps push human–coastal coupled systems toward a new attractor at intermediate timescales that is described by dynamics that are more relational than extractive. We imagine that a new dynamical attractor will likewise manifest at intermediate timescales of years to decades, but the timescale of the transition itself from one dynamical attractor to another – driven by a combination of environmental forcing and market behaviors – is unknown.

Outlook

Coastlines around the world offer us many opportunities to observe relationships between human actions and natural processes – there are few settings in which such interplay is more publicly accessible and readily observable. As a result, the study of human-altered coastlines is not a new science: it has keywords, models, conference sessions, relevant journals, and all the cogs of the modern scientific machine. We offer these questions to encourage new points of departure for research into human–coastal coupled systems, questions that focus on – and beyond – the inevitable threshold that will mark the end of this present era of strong systemic coupling. Bring your hard-soled shoes.

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