

**Hazard mitigation in
coastal human–
environmental
systems**

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Threshold effects of hazard mitigation in coastal human–environmental systems

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Despite improved scientific insight into physical and social dynamics related to natural disasters, the financial cost of extreme events continues to rise. This paradox is particularly evident along developed coastlines, where future hazards are projected to intensify with consequences of climate change, and where the presence of valuable infrastructure exacerbates risk. By design, coastal hazard mitigation buffers human activities against the variability of natural phenomena such as storms. But hazard mitigation also sets up feedbacks between human and natural dynamics. This paper explores developed coastlines as exemplary coupled human–environmental systems in which hazard mitigation is the key coupling mechanism. Results from a simplified numerical model of an agent-managed seawall illustrate the nonlinear effects that economic and physical thresholds can impart into coupled-system dynamics. The scale of mitigation action affects the time frame over which human activities and natural hazards interact. By accelerating environmental changes observable in some settings over human time scales of years to decades, climate change may temporarily strengthen the coupling between human and environmental dynamics. However, climate change could ultimately result in weaker coupling at those human time scales as mitigation actions increasingly engage global-scale systems.

1 Introduction

Beach nourishment, artificial dune construction, and shoreline armoring with rock revetments, bulkheads, and sea walls (Fig. 1) are methods of mitigating coastal hazards in developed coastal zones worldwide. Coastal engineering is an old science, and sea walls are an especially old technology: the Phoenicians used them to protect their ports (Marriner et al., 2006), as did early Chinese dynasties (Qingzhou, 1989). In the UK, coastal defences, including many built during the 19th-century Victorian heyday of English seaside resorts (Tunstall and Penning-Rowsell, 1998), now extend along ap-

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proximately 44 % of the coastline in England and Wales (DEFRA, 2010; BGS, 2012). In the US, shoreline hardening was a common but localized practice that boomed with the post-war housing market of the 1950s, rapidly transforming much of the Mid-Atlantic Seaboard (Pilkey and Wright, 1988). However, even with this legacy, developed coast-

lines illustrate a confounding paradox in the modern science of natural hazards and extreme events: that despite “improved . . . understanding of the physical processes underlying natural hazards and the complexities of social decision-making before, during, and after disasters . . . troubling questions remain about why more progress has not been made in reducing dollar losses” (Mileti, 1999). The UK, the Netherlands, and Belgium still recall “the Big Flood” event of January 1953, a North Sea storm surge that devastated the English east coast and caused an estimated equivalent GBP 5 billion in damage there (Summers, 1978; Johnson et al., 2005; Lombroso and Vinet, 2011). The same storm was so catastrophic to the Netherlands that it prompted the now iconic Delta Plan, a massive national investment in flood-control infrastructure (Gerritsen, 2005). The Big Flood again made recent headlines when the *Guardian* reported a GBP 1 billion funding gap in UK flood-control infrastructure, including coastal defenses, and that the UK Environment Agency has called for a year-on-year funding increase of GBP 20 million just to maintain current protection (Guardian, 2012). On the other side of the Atlantic, Hurricane Katrina, in August 2005, and Hurricane Sandy, in October 2012, rank as the two most expensive weather-related disasters on record for the US (NOAA, 2013). How is it that coastal disasters, which human ingenuity has been trying to ward off for millennia, are presently both better understood and more costly than ever before?

As a thought experiment, “Mileti’s paradox” sets up three hypotheses. First, that extreme weather events, whether through an increasing mean or increasing variability, are becoming more frequent. There is compelling evidence of rising trends in temperature extremes (Rahmstorf and Coumou, 2011) and perhaps in other weather phenomena (Emanuel, 2005; Lubchenco and Karl, 2012). Second, that vulnerable infrastructure and hazard mitigation around the globe is more expensive, beyond inflation, than ever

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before, and thus the higher financial cost of disasters is independent of any trend toward greater extremes in natural systems. Recent growth in high-value development is evident on coastlines worldwide (Cooper and McKenna, 2009). In the US, the per-cubic-yard cost of sand for beach nourishment has risen seven fold since the 1970s (Seabrook, 2013). And third, that a fundamental consequence of hazard mitigation is to filter out small-scale hazard events at the greater expense of infrequent, large ones (Werner and McNamara, 2007). Assessing the risk of a natural hazard involves accounting for the economic value of infrastructure or activities vulnerable to a hazard event, and the probability that an event of a given magnitude will occur. Infrastructural value changes with markets, demographics, and land use, thus changing the risk associated with a given hazard (Mileti, 1999; Smith, 2013). More difficult to anticipate is the effect of hazard mitigation on the magnitude frequency distribution of the hazard itself, which can change even in the context of a stationary climate.

This third hypothesis arises from considering human activities an “Anthropic force” of landscape change (Hooke, 2000; Haff, 2003) that in some cases results in coupled human–environmental systems: contexts in which human activities and the natural physical environment are dynamically linked, such that the state and behavior of each becomes a function of the other. Parsing the complex dynamics of coupled human–environmental systems (also called coupled human–natural systems, coupled human–landscape systems, and coupled social–ecological systems) is a grand challenge in the physical and social sciences (Kates et al., 2001; Haff, 2003; Liu et al., 2007a; Ostrom et al., 2007; Murray et al., 2009; NRC, 2002, 2010; Ostrom, 2010). This paper explores Mileti’s paradox in the context of shoreline protection, a setting in which coupled-system dynamics can manifest over human time scales of years to decades. Synthesizing recent advances in coastal morphodynamics involving feedbacks between human and shoreline processes, I present a numerical model of a seawalled shoreline as a coupled human–environmental system defined by economic and physical thresholds, with implications for the function of threshold structures in managed landscapes more generally.

2 Recent advances in understanding coastal coupled systems

2.1 Beach nourishment

A body of recent numerical modeling research examines the coupled economic–beach dynamics of developed shorelines, with particular attention to beach nourishment (Slott et al., 2008, 2010; Smith et al., 2009; Lazarus et al., 2011; McNamara et al., 2011; Murray et al., 2013; Ells and Murray, 2012; Jin et al., 2013; McNamara and Keeler, 2013; Williams et al., 2013). The work frames beach nourishment as a cumulative cost-benefit optimization problem (Smith et al., 2009), adopting an environmental economics approach typically applied to a renewable resource like timber (e.g. Hartman, 1976). Trees take a certain amount of time to grow into a mature stand. Consequently, in commercial forestry, there is an optimal interval at which trees may be harvested. Harvest them too soon and the timber is worth less money; wait too long and the cumulative return on that patch of forest diminishes. In a coastal town, the width of the beach is analogous to standing timber: the beach constitutes a resource of natural capital (Smith et al., 2009; Gopalakrishnan et al., 2011). A town experiencing shoreline erosion, which depletes that natural capital, may maintain the value of a wide beach through cyclical beach nourishment. Theoretically, like timber harvesting, that nourishment cycle has an optimal frequency: nourishing too often is unnecessarily expensive; waiting too long to nourish results in a narrow beach that negatively affects the town's economic capital. The dynamics of this optimization problem change when a series of towns share the spatial context of a continuous shoreline, such that the management actions of one town begin to affect the beach widths and corresponding management actions of the others. Model scenarios suggest that uncoordinated beach replenishment among neighboring coastal towns may make shoreline erosion rates and mitigation actions more unpredictable, and the use of sand resources more inequitable, as nonlocal effects become more pronounced or unstable in response to forcing conditions associated with climate change, such as sea-level rise and increased storminess.

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2.2 Engineered structures and management decisions as thresholds

Foundational to these beach-nourishment models are two fully coupled, agent-based, dynamic landscape models, one describing the evolution of New Orleans, Louisiana (USA), as a city on a major river delta prone to flooding (Werner and McNamara, 2007), and the other the evolution of Ocean City, Maryland (USA), as a resort town on an eroding barrier island prone to storm-driven overwashing (McNamara and Werner, 2008a, b). Both models demonstrate a boom-and-bust cycle of development and disaster that is an emergent consequence of the human–environmental coupling rather than an intrinsic characteristic of either the economic or physical components of the system. Moreover, thresholds in states of landscape stability, and in development and hazard-mitigation actions by human agents, play an integral role.

In the New Orleans case, artificial levee construction is economically driven; levee height increases in response to flood events that destroy city infrastructure and private property. When flooding destroys property worth more than the cost of levee reconstruction, the levee gets repaired and the local economic market drives property redevelopment. Meanwhile, incremental channelization of the river drives gradual deltaic inundation, increasing the severity of subsequent flood events (e.g. Criss and Shock, 2001). Similarly, in the Ocean City example, resort development and cyclical beach nourishment, driven by tourism economics, restricts natural barrier dynamics by inhibiting the ability of island width and height to change with sea-level rise. When erosion mitigation eventually becomes economically untenable and beach nourishment becomes too infrequent to hold the barrier island in place, the vulnerable resort is destroyed by a storm event and developer agents site new construction on a more stable part of the island where projected economic return is higher.

A key implication of the New Orleans scenario is that “the long-time-scale dynamics of the modeled system appears to be characterized by an attractor with emergent dynamics in which small-scale floods are filtered out at the expense of amplifying the impact of large floods to be significant disasters, because protection from small-scale

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floods facilitates development in areas prone to disaster and increased channelization causes an increase in flood size that results in enhanced damage from the low-frequency flood events” (Werner and McNamara, 2007:404). This same feedback extends to the barrier-island resort scenario, in which “hazard-protection measures filter out high-frequency responses to storms and sea-level rise, but creates long-period boom and bust cycles...” (McNamara and Werner, 2008a:9). The alternative states that arise in these coupled-system examples may be characterized as “undamaged” and “damaged”, with long periods of the former punctuated by sudden episodes of the latter. Dynamical systems discourse defines thresholds in terms of transitions between alternative states (Abraham and Shaw, 1988; Scheffer, 2009), a definition that ecology-based perspectives of coupled human–environmental systems have tended to adopt (Beisner et al., 2003; Groffman et al., 2006; Liu et al., 2007a, b; Chin et al., 2013). But from a geomorphology-based perspective, engineered hazard-mitigation structures like artificial levees and sand dunes, beach nourishment, and seawalls also function as physical thresholds: imposed barriers that a hazard must erode, crest, or breach before it can interact (through flooding, erosion, sediment transport, deposition) with the otherwise sheltered landscape. The threshold between dynamical states is thus the mitigating barrier itself, filtering the impact of high-frequency events but literally breaking down with low-frequency recurrence.

Formal definitions of coupled human–environmental systems emphasize the importance of feedbacks that link human activities and natural processes (Turner et al., 2003; Liu et al., 2007a; Chin et al., 2013), but none addresses feedback reciprocity and strength more specifically than the description by Werner and McNamara (2007:399), who write that 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,

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evaluate profits from those investments, and respond to changes in conditions.” This definition categorically distinguishes coupled systems from, for example, extractive resource activities that obviate or ignore preventative measures against damage (e.g. McDaniel and Gowdy, 2000). Furthermore, Werner and McNamara (2007) associate strong human–landscape coupling with environmental hazard and risk, which distinguishes their definition from others derived more from social complexity in common-pool resources (e.g. Ostrom, 2010). Coastal environments offer such accessible examples of strongly coupled dynamics because risk exposure to natural hazard is arguably an inherent characteristic of developed coastlines (e.g. Nordstrom, 2000; Kelley and Brothers, 2009). Seawalls, for example, are a ubiquitous response to coastal hazard and risk associated with shoreline erosion and storm surge. Controversy regarding seawalls as a coastal management practice tends to hinge on whether a seawall exacerbates shoreline erosion (Kraus, 1988; Pilkey and Wright, 1998; Kraus and McDougal, 1996; Dean and Dalrymple, 2002), but more broadly, the role of seawalls may be interpreted in terms of a managed physical threshold within a coastal coupled system.

3 Example: threshold dynamics in a seawall model

A deliberately simplified, one-dimensional numerical model demonstrates how a seawalled shoreline may exhibit system dynamics similar to those described for leveed rivers (Criss and Shock, 2001; Werner and McNamara, 2007) and artificial dune fronts on barrier islands (Magliocca et al., 2011). The model combines mechanical interaction between the beach and seawall with decisions by a coastal-manager agent regarding seawall construction and repair. Rather than simulating a particular place, the model represents coupled-system dynamics of seawalls in abstracted terms.

scale of the storm (S) and the product of wall height multiplied by wall strength:

$$D_{\text{storm}} = S - (W_H \times W_S) \quad (2)$$

Wall strength is adjusted by both the storm damage and annual deterioration related to beach width:

$$W_S^{t+1} = W_S^t - (\rho + D_{\text{storm}}) \quad (3)$$

where t is the model time step (year). If S is less than the product of W_H and W_S , then $D_{\text{storm}} = 0$.

3.1.2 Hazard mitigation

Hazard mitigation actions affect wall height and wall strength. When the model begins, the initial wall height is set equal to the scale (S) of the first storm. Subsequent increases in wall height and repairs to wall strength are reactionary, lagging storm impacts. As a record of storm-driven wall damage develops, the coastal-manager agent interprets the record to make decisions about whether or not to repair the wall. When repaired, the wall is always restored to full strength ($W_S = 100\%$), and wall height is determined by the largest storm on record ($W_H = S^*$).

The manager's decision process goes as follows. Each year, the manager looks back over the previous N storms that caused wall damage, plots the damage sustained (D_{storm}) against wall strength at the time of the storm for those N events, and calculates a best-fit linear trend through the data points (Fig. 3). The manager requires hindsight of $N > 1$ damage events in order to calculate a line, and the best-fit line needs a negative slope to be physically meaningful (e.g. damage is high when wall strength is weak); hindsight of $N > 4$ prevents nonsensical trend calculations. Given a best-fit line, mitigation action then depends on two thresholds: a damage tolerance (D^*), meaning that damage exceeding D^* warrants mitigation, and a second threshold requiring that wall strength must be degraded beyond a certain percentage (W^*) for repairs to be

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considered cost effective. In real coastal management settings, fixed costs associated with work crews, equipment, and permitting make capital-works projects like seawalls subject to economies of scale (e.g. Leafe et al., 1998; Smith et al., 2009). This component of the model reflects the relationship between scale of repair and cost distribution.

5 The manager finds where the calculated best-fit line intersects the ordinate line D^* . If the abscissa of the intersection is greater than W^* , then wall repair is deemed cost effective. Indeed, if this condition is satisfied, then repairs to all wall conditions between W^* and the abscissa intercept of the best-fit line are cost effective (Fig. 3). This window of cost effectiveness varies each time the manager recalculates the best-fit line. If
10 the abscissa for the best-fit intersection with D^* is less than W^* , the condition for cost effectiveness is not satisfied and the wall is not repaired that year. Both D^* and W^* are imposed constraints, and remain fixed for the duration of a model run.

3.2 Results

Figure 4 is a representative example of how key parameters in the model change over
15 time: the occurrence of record-setting storms; increases in seawall height; years punctuated by storm-driven damage; and the threshold of cost effectiveness for wall repair calculated by the manager agent. Because the model assumes a stationary climate (zero trend in storm magnitude or sea-level rise), more extreme events occur in the beginning of the time series: the likelihood of an unprecedented extreme (a maximum
20 value in the time series) declines with $1/t$, where t is the number of previous years in the time series (Rahmstorf and Coumou, 2011). This quick succession of impactful storms drives early investment in wall construction until wall height is nearly equal to the largest possible storm event. When the wall is low, storm damage is almost always extensive enough for the manager to opt for wall investment. Annual storm damage
25 decreases as the wall gains height and serves as a more effective barrier against a greater range of storm events.

If the wall did not deteriorate, here the model would effectively stop. Oppositely, if left unrepaired (and in the absence of major storms), the model seawall degrades within a

domized forcing conditions. In the left column, color represents the difference between total storm damage and total wall investment over the duration of a model run; in the right column, color represents standard deviation in the ensemble results. The totals in Fig. 6 illustrate in aggregate what the trajectories in Fig. 5 capture in detail. Minimizing seawall deterioration in the model is an effective but expensive preventative measure against storm damage. Oppositely, infrequent wall repair costs less overall but comes at the expense of large amounts of damage. Moreover, when repairs do happen, they require maximum expenditure. The longer the data series (N) the manager agent uses in the decision calculations, the lower the variability in the system outcome: a best-fit line through 30 data points changes less from year to year than a line through five points, tempering the extremes of damage and investment costs over time.

Of course, this model does not simulate the fine-grained intricacy of real shoreline management. Among the model's limitations, a single manager agent treats the seawall as a single managed unit, where a long seawall might be repaired in parts and can extend across adjacent municipalities. Also, the manager agent's decision-making process operates within the imposed bounds of fixed parameters for damage tolerance and economy of scale. But even if those thresholds varied as a function of property value, for example, the results shown still illustrate the kinds of patterns a resulting time series would comprise. A trend of increasing property value might drive increased investment in mitigation and thereby decrease total incurred damage (e.g. Fig. 5a). A decline in property value might make hazard mitigation less relevant, and the seawall might be left unrepaired for long periods (e.g. Fig. 5c). The value here of exploring the model's parameter space in discrete pairs of bounding conditions is that the underlying mechanisms for system behaviors remain transparent.

The premise does assume sustained managerial commitment to a seawall (e.g. Pilkey and Wright, 1988) and does not explore cost-benefit conditions for abandonment (e.g. McNamara and Keeler, 2013). Strangely enough, the manager's hindsight-based approach to decision making has a surprising, if dubious, recent precedent: in June 2012, the state Senate in North Carolina, USA, passed a bill requiring that state

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farther the system’s net benefits drift from the optimal outcome (e.g. Lazarus et al., 2011). The seawall model presented here illustrates increased systemic variability in response to frenetic management recalculations (Figs. 5 and 6), even under stationary forcing conditions. The trajectory shown in Fig. 5b, and the regions of the model parameter space where the difference between total damage and total investment hovers around zero in Fig. 6, represent a managed coastal system unwilling to tolerate damage but reluctant to invest in the scale of infrastructural maintenance necessary to prevent it. By contrast, of any managed coastline in the world, the best example of a long-term optimization strategy in practice must be the Netherlands, whose damage-versus-investment trajectory might look more like Fig. 5a. The Dutch Delta Plan has engineered Mileti’s paradox into a moot point: the coastal hazard is well understood, the cost of maintenance is high but accepted, and the resulting cost of damage is small.

Although the Delta Plan is a physical threshold of such magnitude that impact from all but the rarest events are preventatively filtered, it is not a solution to sea-level rise. Therefore, the scale of intervention on the Dutch coast has not decoupled human dynamics from natural environmental processes so much as coupled them to the environment at a time scale significantly longer than those most governments treat as dynamically relevant. Such contrasting scales of intervention complicate the suggestion that “climate change, by accelerating the rates of landscape change, tends to strengthen the coupling with human dynamics” (Murray et al., 2013:30). With various technological innovations throughout history, humans have proven remarkably successful at weakening the strength of coupling between human and environmental dynamics. For example, land clearing in pre-Columbian Mesoamerica triggered intensive soil erosion, but agricultural terracing – another physical-threshold system – was so effective at preventing subsequent soil loss that the next spike in erosion only occurred after the landscape was abandoned and the terrace structures began failing from lack of maintenance (Fisher et al., 2003). Other innovations have made uninhabitable places habitable, resulting in development that is functionally disconnected from surrounding natural systems: consider what air conditioning makes possible by masking outdoor heat

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and humidity, or that cities in arid basins can divert water from major river drainages over huge distances (e.g. Hundley, 2009). Technological disconnection from local environmental conditions allows an anthropic “built layer... of artificial composition and structure” to be superimposed on the Earth’s surface (Haff, 2003:19). Writ larger, the frontier of innovative environmental interventions has reached the scale of geoen-

In light of this technological track record, in the near term, climate change may strengthen coupling with human dynamics in systems that are already strongly coupled: settings in which mitigation actions such as river levees (Chriss and Shock, 2001; Werner and McNamara, 2007), artificial dunes (Magliocca et al., 2011), beach nourishment (Lazarus et al., 2011), and seawalls match rather than overwhelm natural system processes. Given what contributes to strong coupling (Werner and McNamara, 2007), it follows that coupling strength is an inherently transient property of coupled systems. If institutions invest in mitigation infrastructures that function as physical thresholds on the scale of Earth’s global systems, climate change could ultimately reduce, rather than increase, coupling strength observable over human time scales.

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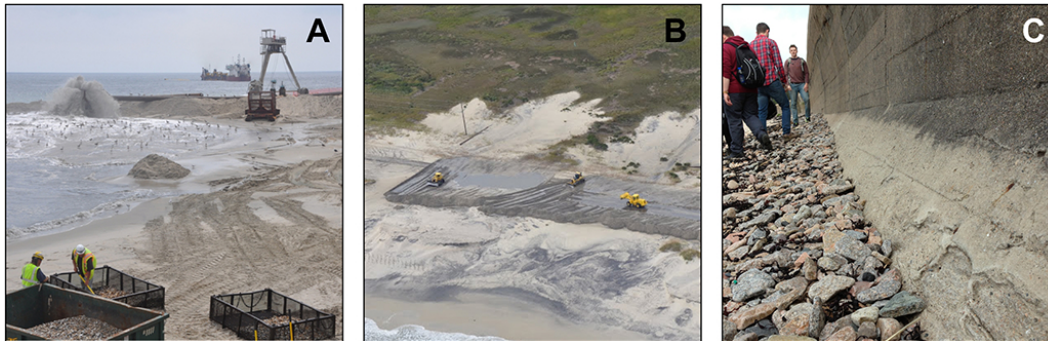


Fig. 1. Three examples of typical coastal hazard mitigation practices: **(A)** beach replenishment in Monmouth, New Jersey (USA), nine months after Hurricane Sandy (photo: A. Coburn, Program for the Study of Developed Shorelines, <http://www.psds-wcu.org/>); **(B)** artificial dune reconstruction following an overwash event on Highway 12, North Carolina Outer Banks (USA) (photo: A. Coburn, PSDS); **(C)** concrete seawall on the Channel Island of Jersey – note the pitting and fresh scour (light gray band) along the wall base just above the shingle toe.

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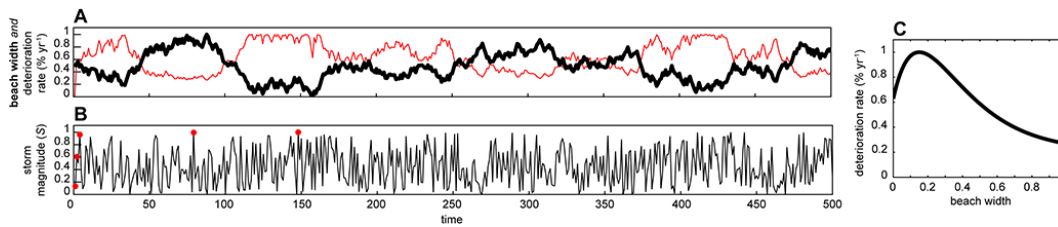


Fig. 2. Forcing components for the seawall model. **(A)** Normalized Brownian signal representing beach width over time (bold) and the corresponding wall deterioration rate (red). **(B)** Randomized time series of storm events over the simulation period (500 yr); red dots mark record-setting storms. **(C)** Plot of wall deterioration rate as a function of beach width, motivated by Limber and Murray (2011), Strudley et al. (2006) and Anderson (2002).

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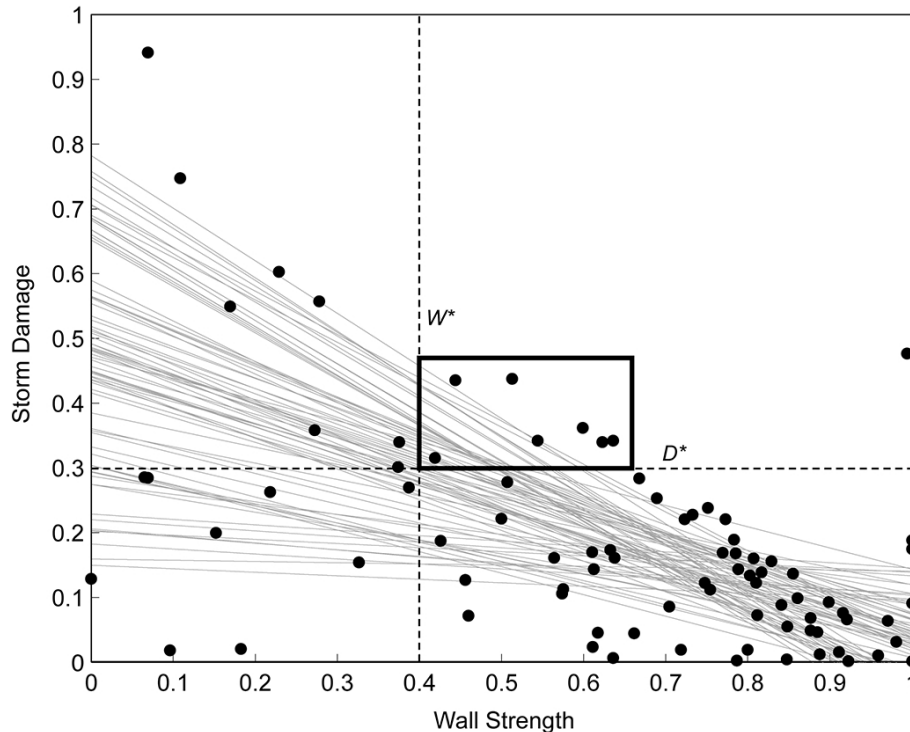


Fig. 3. The manager agent uses a line of best fit relating storm damage to wall strength for the previous N damaging storm events to determine whether wall repairs are cost effective, given imposed thresholds for damage tolerance (D^*) and economy of scale (W^*). In this plot ($N = 10$ events), damage must exceed $D^* = 0.3$, and at least 40% of the wall ($W^* = 0.4$) must have deteriorated to warrant repair. Lines of best fit that satisfy these conditions pass through the box shown in bold.

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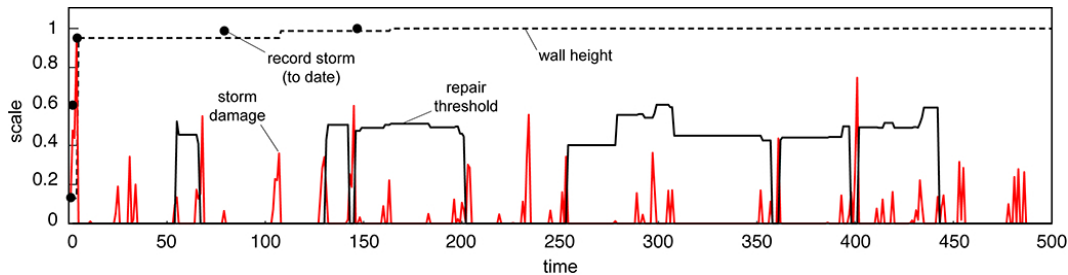


Fig. 4. Representative time series of key model parameters (where $D^* = 0.3$, $W^* = 0.4$, and $N = 10$): record-setting storms (black dots); seawall height (dashed line); storm-driven damage (solid red line); and the threshold of cost effectiveness for wall repair calculated by the manager agent (solid black line).

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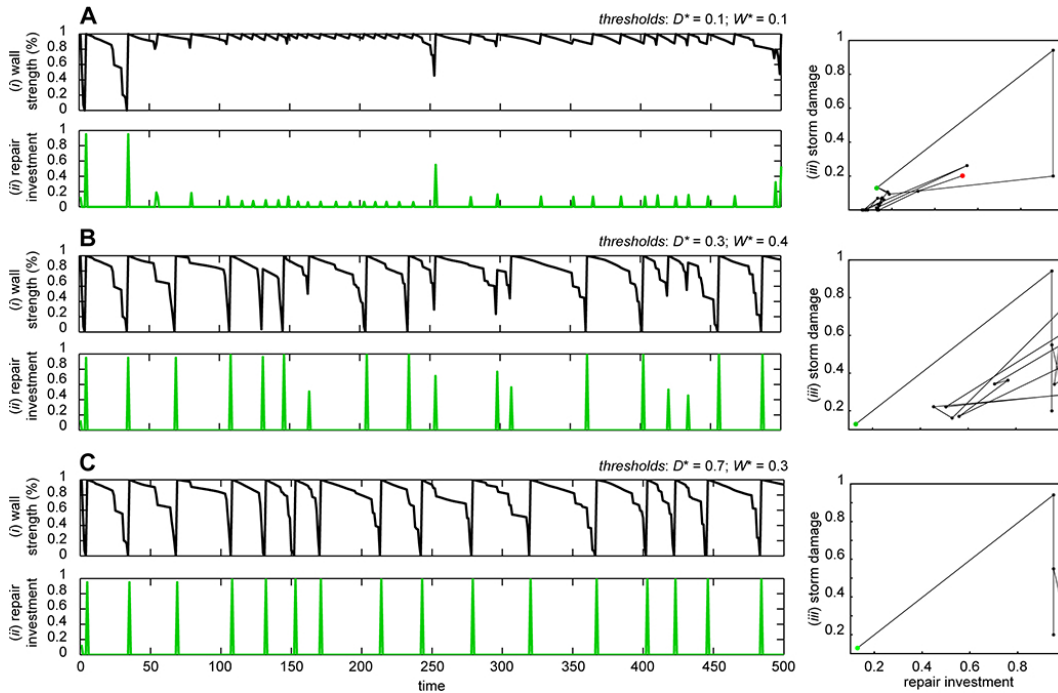


Fig. 5. Time series of wall strength and storm damage, and the trajectory of those parameters with respect to each other (where green and red dots mark the beginning and end of the data series, respectively), for three representative pairs of threshold conditions in which: **(A)** thresholds for damage tolerance and economy of scale are both low ($D^* = 0.1$ and $W^* = 0.1$); **(B)** both thresholds are intermediate ($D^* = 0.3$ and $W^* = 0.4$); and **(C)** damage tolerance is high and the economy of scale is intermediate ($D^* = 0.7$ and $W^* = 0.3$). In all three cases shown, $N = 10$ events.

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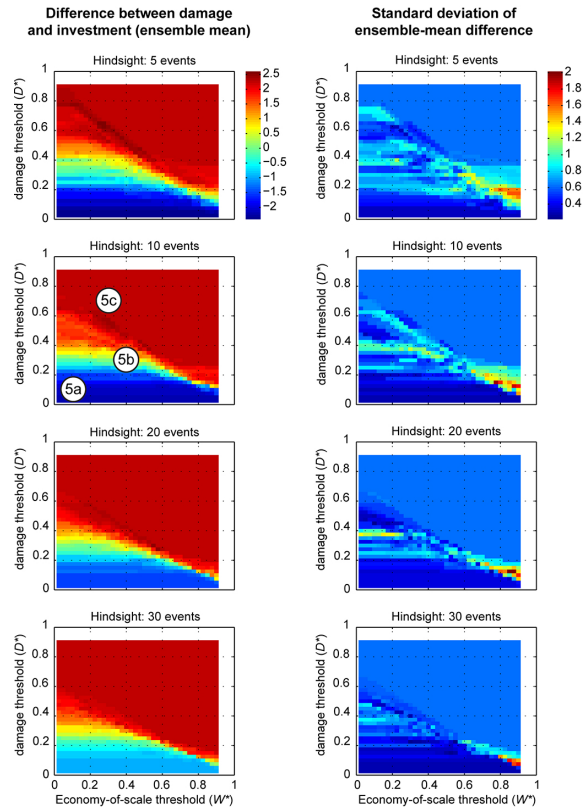


Fig. 6. Parameter spaces of threshold pairs D^* and W^* for four hindsight conditions ($N = 5, 10, 20, 30$). In the left column, color represents the ensemble-mean difference between total storm damage and total investment in repair (derived from ten different randomized forcing time series for beach width and storms, as in Fig. 2). In the right column, color represents standard deviation around each ensemble mean. Numbered circles indicate parameter pairs shown in Fig. 5.

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