Control of natural hazard events through emergency landscaping

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Key Points

1. Emergency landscaping refers to deliberate, concurrent, mitigating interventions in the physical processes of a natural hazard event.
2. A theory for emergency landscaping serves as a tool to identify signatures of intervention actions across natural hazard systems.
3. Insight into emergency landscaping phenomena may help narrow the gap between prediction and observation in natural hazard modelling.

Abstract

Humans reshape the surface of the Earth through efforts to protect people and places from natural hazards. While some hazard defences, such as river levees, are permanent infrastructure, other measures, such as wildfire fighting, are responsive: they occur while a hazard event is in progress, actively intervening in its behaviour to mitigate its impact. Deliberate, concurrent, mitigating interventions in the physical processes of a natural hazard event are here termed "emergency landscaping". When intervention actions are concurrent with an evolving natural hazard event, hazard and intervention behaviours may become mechanistically coupled, such that each changes as a function of the other. Despite their ubiquity across a variety of natural hazard types and settings, emergency landscaping is missing from process-based, predictive numerical models of natural hazard events that inform operational decision-making. Improving prediction of natural hazard impacts is fundamental to reducing disaster risk. For hazard events that trigger intervention, eliding the effects of emergency landscaping may contribute to persistent disparities between model prediction and observation. Addressing emergency landscaping as a fundamental physical process in human-altered environments opens new avenues of interdisciplinary research into the dynamics of natural hazards.

Plain Language Summary

Many kinds of natural hazard events trigger emergency responses that intervene directly in the progress of the hazard itself. Wildland firefighters are deployed to control wildfires; bulldozers clear beachfront roads during coastal storms; volunteers stack sandbag levees during floods; water may be pumped onto lava flows to slow them down. I term these deliberate, concurrent, mitigating interventions in the physical processes of a natural hazard event "emergency landscaping". Intervention actions during a hazard event can alter the behaviour of the hazard, and vice versa. Yet despite their ubiquity in practice, such interventions are still missing from numerical models used to predict the physical impact of natural hazard events. This is important because efforts to reduce disaster risk rely on accurate predictions of natural hazard impacts, especially in developed settings. Just as fire spread, sediment transport, and flood propagation are physical processes of natural hazard events, understanding emergency landscaping as a physical process may help narrow the gap between prediction and observation in hazard modelling.

1 Introduction

Humans alter physical environments across the surface of the Earth, reshaping landscapes to suit societal needs and preferences (Hooke, 1994; Nordstrom, 1994; Haff, 2003; Ellis, 2011; Ross et al., 2015; Firth et al., 2016). The need to protect people, assets, infrastructure, and land uses from natural hazards reshapes landscapes through the implementation of hazard defence. Levees, dikes, and seawalls, for example, reshape river and coastal floodplains to control flooding and erosion. Many defensive works are permanent and precautionary, built and maintained in the quiescent periods between hazard events. But other forms of hazard defence are temporary and responsive: they occur during a hazard event, and involve active interventions that alter the physical environment with which the hazard interacts. Examples of this responsive mode include cutting firebreaks at the burning front of a wildfire (Plucinski, 2019a, 2019b; Hirsch & Martell, 1996), plowing sand into a fronting dune during a coastal storm (Lazarus & Goldstein, 2019), stacking sandbags during a river flood (Padgham et al., 2014), and hosing down a lava flow to slow its advance (Williams & Moore, 1976) (**Fig. 1**). Here, I term these deliberate, concurrent, mitigating interventions in the physical processes of a natural hazard event "emergency landscaping" (Venton, 2018).

While a permanent defence steers the outcome of a hazard by passive obstruction, emergency landscaping does so dynamically, by altering local physical conditions at the hazard interface. Emergency landscaping actions are sensitive to the behaviour of the hazard event in order to make the hazard event sensitive to emergency landscaping. Attempting this inversion creates the potential for hazard and intervention behaviours to become mechanistically coupled. For example, during a coastal storm, using a bulldozer to plow sand into gaps in a fronting dune diverts local pathways of storm-driven water flow and sand deposition, which informs where the bulldozer must next direct its efforts (Lazarus & Goldstein, 2019). Knowing whether emergency landscaping may result in strong, weak, or no mechanistic coupling is crucial for predicting the behaviour and impact of a hazard event that triggers intervention.

This mechanistic coupling, however, can make it difficult or impossible to predict the evolution of the hazard event, because the intervention systemically alters how the hazard event develops. This is important because predictive hazard models inform everything from emergency management and urban planning to insurance instruments and reinsurance markets (Grossi et al., 2005; Merz et al., 2020). At the interface of natural and built environments – within a fire ecology (Radeloff et al., 2018), along a coastline (Lazarus et al., 2016), on a river floodplain (Di Baldassarre et al., 2013), or downslope of an active volcano (Williams & Moore, 1976) – is where predicting hazard impacts is both most essential and most challenging (Haff, 2003, 2013). The adaptive capacity of a human–landscape coupled system (Werner & McNamara, 2007) presents a fundamental limit to predicting hazard impacts because the full array of possible system states may be unknown, or unknowable (Batty & Torrens, 2001; Levin, 2002; Beckage et al., 2011; Haff, 2013; Hofman et al., 2017; Mertz et al., 2020; Bates, 2022). State-of-the-art models of natural hazards might incorporate hazard defences or mitigating actions as either fixed preconditions or *post facto* responses. But (to the best of my knowledge) no numerical model for high-fidelity simulation of a natural hazard at the event scale includes mechanisms of concurrent human intervention, despite the variety and ubiquity of such interventions in practice. Understanding emergency landscaping as a physical process – that is, a way in which humans function as agents of geomorphic change (Hooke, 1994; Haff, 2003, 2010) – will enable the exploration of a greater range of possible states and behaviours in natural hazard systems, and is critical to improving hazard predictions at the event scale.

To examine emergency landscaping as a systemic phenomenon, I expand upon my definition with examples of emergency landscaping in different natural hazard systems. From those examples, I offer a theory for emergency landscaping as a tool to identify signatures of intervention across hazard systems that tend to be obscured or overlooked. To demonstrate, I show an exploratory numerical model that explicitly incorporates emergency landscaping into a hazard event, and highlights many of the enigmatic behaviours of emergency landscaping as an adaptive physical process in human-altered environments. I also outline research directions for further inquiry.

2 General definition of emergency landscaping

I define emergency landscaping as deliberate, concurrent, human intervention in the physical processes of a natural hazard event to mitigate its impact. Intervention actions must be deliberate, with the aim to divert, contain, or dissipate the hazard event. To function, an emergency landscaping intervention must mobilise faster than the onset of the hazard, or progress faster than the hazard, or both. Actions may be coordinated and systematic, such as the work of many wildland fire crews responding to a large wildfire, or *ad hoc*, such as plugging an isolated levee breach during a flood. Concurrence is essential to emergency landscaping because if intervention occurs during the hazard event, there is potential for hazard and intervention processes to become mechanistically coupled, such that the behaviour of each is a function of the other.

3 Examples of emergency landscaping

To illustrate this definition of emergency landscaping, I offer several examples and describe how each represents a mode of deliberate, concurrent intervention into natural hazard processes at the event scale.

3.1 Wildfires

Wildfire crews alter landscape conditions during a wildfire to mitigate its impact. These crews may meet a wildfire directly, with methods that put out the fire from the ground or air, such as with water or chemical suppressants; or they may work to suppress the fire indirectly, by clearing brush, digging trenches, and plowing control lines to establish deliberate firebreaks that constrain the fire perimeter (Plucinski, 2019a, 2019b). Wildfire containment or suppression in real time is distinct from preventative mitigation measures, such as prescribed burning and forest thinning (Davis et al., 2024; Brodie et al., 2024), which occur between wildfire events.

A wildfire crew must adapt its actions to the behaviour of the wildfire. But wildfire behaviour also changes with active suppression – at least for fires below a certain intensity or magnitude (Cruz et al., 2018; Plucinski, 2019a). This reciprocity indicates a potential for process coupling. Reducing burnable fuel along segments of the fire perimeter or steering a fire toward topography favourable for containment reduces fire intensity, and, by extension, the local rate of fire spread. Potential for coupling may depend on the rate of containment relative to the rate of spread, or nonlinearity in the relationship between the rate of containment and the rate of spread, or changes in the external forcing conditions (Hirsch & Martell, 1996; Plucinski, 2019a, 2019b). However, wildfire crews cannot be everywhere at once: while one segment of the fire perimeter gets suppressed, another may gain ground. Targeted actions along segments of the fire perimeter may collectively change the behaviour of the fire at larger spatial scales, which can cause modelled forecasts to diverge from observed wildfire behaviour (Coen et al., 2020; Zhou et al., 2024). Here, forecasting does not refer to the likelihood of fire occurrence, but rather how a wildfire is likely to evolve in space and time. Although there are examples of agent-based and probabilistic models that represent or parameterise the effects of suppression on wildfire spread (Duff & Tolhurst, 2015; Plucinski, 2019b), explicit integration of firefighter actions into wildfire dynamics remains an aspiration for improved operational wildfire forecasting at incident and landscape scales (Taylor et al., 2013; Duff & Tolhurst, 2015; Cruz et al., 2018; Plucinski, 2019b; Ford et al., 2021).

For wildfires at the wildland–urban interface, where built structures are situated within a vegetated wildland, that modelling challenge is magnified. (The wildland–urban interface is a term that extends to exurban and rural areas (Stewart et al., 2007).) Wildfire risk is disproportionately higher at the wildland–urban interface because human activities impart a higher likelihood of ignition (Radeloff et al., 2018). Because these settings host more lives, livelihoods, and infrastructure than wildlands, firefighting crews are likely to be called upon to protect them. However, predictive modelling of fire spread at the event scale is complicated at the wildland–urban interface by heterogeneities in the built footprint, structure ignitability, and the distinctly anthropic spatial ecology of vegetation species within built environments (Syphard et al., 2019; Ganteaume et al., 2023), which make wildland–urban fires behave differently from their natural counterparts (Coen et al., 2020). Measurements of containment rates for wildfires – the rate, in units length per time, at which a handcrew can clear a control line, for example – derive from wildland settings (Plucinski, 2019a, 2019b); containment rates for wildland–urban fires likely require independent determination.

3.2 Coastal storms

In low-lying coastal settings, public-works crews tasked with maintaining the functionality of beachfront road networks will use fleets of heavy machinery – front-end loaders, bulldozers, graders – to clear sediment washed or blown onto roadways (Nordstrom, 2004; Lazarus & Goldstein, 2019). If crews work while a storm is in progress, as opposed to before (Harley & Ciavola, 2013; Gallien et al., 2015) or after (Nordstrom & Jackson, 1995), then their actions become a concurrent intervention into sediment-transport processes at time scales shorter than the storm event (Lazarus & Goldstein, 2019). This creates the conditions for process coupling. During a storm, the mechanics of sediment transport over local topography naturally create a feedback: topography directs flow, which affects spatial patterns of sediment erosion and deposition, which reshapes topography, which redirects flow. Using a bulldozer to intervene in patterns of storm-driven deposition introduces an anthropic physical mechanism of sediment transport (Haff, 2010). As both the bulldozer and the storm-driven flow rework the terrain simultaneously, each mechanism affects patterns of erosion and deposition shaped by the other.

This coupling means that a numerical model of storm impact that is predicated only on pre-event conditions, however detailed and timely those input data may be (Sherwood et al., 2022), will likely deliver a result that diverges from the storm impacts ultimately observed. Such divergence between storm impact prediction and observation may matter more for localised, storm-specific forecasts than for projections of coastal change over longer and larger spatial and temporal scales. Furthermore, the window of process coupling may be relatively brief. If road crews stop working because storm conditions become too dangerous, then subsequent pulses of storm-driven flow may obscure physical evidence that mechanistic coupling occurred. Regardless, as yet, no off-the-shelf model of coastal dynamics capable of resolving detailed landscape change at the event scale accounts for deliberate, concurrent, dynamic interventions into storm-driven sediment transport (Lazarus & Goldstein, 2019).

3.3 River flooding

River flooding can be contained, steered, or diverted during a flood event through various temporary measures. One is with sandbags or sandbag replacement systems (Massolle et al., 2018; Lankenau et al., 2019). Deployed during the rising limb of a flood event, they constrain the footprint of flood inundation by channelising flood water or blocking its lateral spread. Although localised, sandbagging and its variants change the effective height of channel banks and floodplain terrain, and therefore alter potential flow pathways. Emplaced immediately before flooding and removed afterward, they are absent from assessments of flood defences and infrastructure inventories upon which predictions of flood inundation rely (Wenger, 2015; Bates, 2022, 2023).

Another concurrent intervention in river flooding involves detonating fuse plugs in a channel levee. Blasting a deliberate breach during a critical phase of the flood event may divert floodwaters toward accommodation space in a floodplain (Jaffe & Sanders, 2001; Olson & Morton, 2012; Londoño & Hart, 2013). To effect the greatest reduction in flood inundation or extent, the locations of deliberate levee breaches can be modelled probabilistically (Wallace et al., 2023), but deliberate breaches are not typically integrated into flood inundation forecasting. Where levee breaches are unintentional, viral videos across the internet record cases of people driving sediment-laden vehicles – from pick-up trucks to lorries – into free-flowing breaches in attempts to close them (Alexander, 2023).

Emplacement of sandbags or a temporary levee along one river reach might affect flood stage along another (Heine & Pinter, 2012) – perhaps enough to also trigger temporary levee emplacement there, or result in an unexpected diversion of floodwater that prompts additional *ad hoc* containment (Leavitt & Kiefer, 2006). This patchwork proliferation of local interventions with nonlocal effects on flood behaviour may be the primary mechanistic feedback associated with temporary levees.

3.4 Lava flows

Popularised by John McPhee in his book *The Control of Nature* (1987), perhaps the most famous example of emergency landscaping during a volcanic hazard event took place in Iceland, during the effusive eruption of the Eldfell volcano in 1973. The fishing port of Vestmannaeyjar, on the island of Heimaey, was saved from total destruction through an ambitious and coordinated effort to cool, slow, and steer an advancing effusive lava flow by hosing it down with seawater (Williams & Moore, 1976; Siguresirsson, 1997; Williams, 1997). Another means of steering and controlling active lava flows, variously attempted in the last century, is aerial bombing or detonation of placed explosives (Lockwood & Torgerson, 1980; Barberi et al., 1993).

In the same way that temporary levees are distinct from permanent flood-control structures, concurrent interventions in the physical processes of effusive volcanic eruptions are distinct from passive measures to steer, divert, or contain lava flows with constructed barriers and artificial levees (Fujita et al., 2009; Dietterich et al., 2015). (Similar kinds of passive measures are also used to contain debris flows (Hungr et al., 1987; McPhee, 1987)). An exceptional case might be the variety of interventions, including temporary barriers, used to divert lava away from the village of Zafferana Etnea, during the 1991–1992 eruption of Mt. Etna (Barberi et al., 1993). There, once the threat to the village became apparent, a series of earthen barriers were constructed, with increasing haste, along the flow path to contain the flow on the upper slopes of the mountain flank. As these earthen barriers were sequentially overwhelmed, intervention efforts shifted to a difficult, multi-faceted plan for channel diversion that was ultimately successful.

Potential mechanistic feedbacks between intervention actions and effusive lava flows may be related to those in river systems with temporary levees. In the Zafferana Etnea case, progress of the lava flow motivated construction of a barrier to alter the landscape of the flow path; the resulting interaction between the lava flow and that initial barrier set off an escalating series of additional steering actions downslope. On Heimaey, water-cooling actions that started at the lava front and leap-frogged up-flow were a way to use the lava to dam itself. But weeks into the water-cooling effort, a lateral splay avulsed from the arrested body of the main flow and surged into the town of Vestmannaeyjar. Whether that change in flow behaviour was an unintended consequence of the cooling actions is a point of speculation (McPhee, 1987), but if so, the avulsion would be indicative of mechanistic coupling and an example of spatially localised interventions having a nonlocal effect on hazard behaviour.

3.5 Other examples

A variant on permanent river or coastal levee systems are mobile or gated storm-surge barriers, which are devices installed across inlets or estuary mouths to protect urbanised hinterland from sea flooding (Orton et al., 2023). These systems are intended to allow free exchange of water, nutrients, and sediments unless deliberately activated on the rising limb of a tide or surge to block the landward incursion of an extreme high-water event. Although their landscape-altering effects are less obvious than those of a bulldozer, mobile barriers nonetheless force concurrent changes in the hydrodynamics of a flood event, and therefore on the circulatory pathways of nutrients and mineral sediment within the estuary system (Tognin et al., 2021, 2022). While other forms of emergency landscaping involve decisions regarding where to deploy responsive actions and at what scale, with operations that cycle through rounds of iterative decision-making during a single hazard event, surge barriers are dynamic permanent structures that are triggered once, at the onset of a flood event. This makes surge barriers sensitive to a storm event, but insensitive to mechanistic coupling with hydrodynamics at the event time scale. However, coupling between surge barriers and self-regulating estuarine processes may emerge over longer time scales spanning multiple storm events. For example, reduced storm-driven sediment supply within the estuary might limit tidal marsh accretion, gradually deepening the tidal prism within the estuary, and thus require more frequent activation of the surge barriers to prevent flooding in the urbanised hinterland (Mel et al., 2021; Michieletto et al., 2025).

Emergency landscaping may also extend to attempted interventions into drought, such as rainfall enhancement through cloud seeding (Flossman et al., 2019; Abshaev et al., 2022; Wehbe et al., 2023) and dryland afforestation (Liu et al., 2022; Tuinenburg et al., 2022; Stavi et al., 2024). As droughts are a slow hazard, deliberate manipulation of meteorologic and hydrologic conditions over commensurate time scales might be considered concurrent intervention, with potential mechanistic feedbacks involving plant ecology, soil, groundwater, and other physical environmental systems.

4 Building a theory of emergency landscaping

These examples of emergency landscaping lend themselves to more formal comparison. For natural hazards that exhibit a rate of propagation, emergency landscaping may be characterised by a rate of containment. For wildfires, for example, the rate at which a wildfire crew can cut a control line decreases nonlinearly with wildfire intensity (Murphy et al., 1991; Hirsch & Martell, 1996) (**Fig. 2a**). The rate of containment is inversely related to the magnitude of the hazard forcing.

This inverse relationship is likewise expressed in other hazard systems (**Fig. 2b, c, d**). An exploratory numerical model in which a bulldozer reinforces a fronting dune during a coastal storm (see **Box 1**) shows that plowing actions become less effective as storm forcing increases (Lazarus, 2025, 2026) (**Fig. 2b**). In the model, storm intensity is represented by the frequency with which sand is washed through the dune line. Forcing during a trial is held constant, as is the speed and plowing capacity of the bulldozer. Trialled across a range of forcing frequencies, the model shows that if the time interval between pulses of sand is sufficiently long, the bulldozer can keep the floodplain behind the dune clear enough to achieve a reasonably high rate of containment. Conversely, storms with short intervals between pulses deliver sand to the floodplain faster than the bulldozer can plow it away.

For sandbag levees, practical guidance advises using a pyramid construction, such that the required number of sandbags per unit height increases quadratically (USACE, 2022). Meanwhile, there is an approximate maximum rate at which a human team can manually prepare sandbags (EA, 2009). These two equivalencies yield a relationship for the rate-of-rise of a sandbag levee – in the absence of a sandbag stockpile – at a single point on the channel bank. Comparing this estimated rate-of-rise for a sandbag levee against daily average rate-of-rise data for flows over bankfull from four gaging stations in England indicates a steeply nonlinear inverse relationship (**Fig. 2c**). The respective rates suggest that, assuming concurrent intervention, a sandbag levee at these stations theoretically could be raised faster than the daily average rate-of-rise for most of the flood stages on record – but not fast enough to contain a flash-flood event (Archer & Fowler, 2018).

Indications of an inverse relationship between containment and hazard propagation are also evident in effusive volcanic eruptions. An exploratory study of a single eruptive event on Izu-Oshima, in Japan, used a numerical model of effusive lava flow to investigate the effect of a hypothetical water-cooling intervention on lava flow (Fujita et al., 2009). In the model, water cooling is introduced at a point-source in the flow path, downslope of the eruption source. Once the flow front encounters the intervention, the flow slows and relative containment increases until the flow grinds to a halt (**Fig. 2d**). This result suggests that modelling many Izu-Oshima events for a range of possible lava flow velocities would result in a containment curve similar to that in the coastal example (**Fig. 2b**).

In generic terms, circumstances in which the rate of containment exceeds the rate of hazard propagation may be described as being intervention-dominated; in contrast, circumstances in which the rate of propagation exceeds the rate of containment may be described as hazard-dominated (**Fig. 3a**). The shape of the curve relating the two rates may change during an event, even under constant forcing conditions **(Fig. 3b)**. For example, the rate of containment might decline with time due to fatigue or resource limitations; or the rate of containment might increase with combined modes of intervention, such as when handcrews, mechanised crews, and air support converge on the same active wildfire front (Plucinski, 2019b).

A dimensionless metric (*E*) reflects, at least to the first approximation, the efficacy of emergency landscaping in a given event, represented as the ratio of the rate of hazard propagation to the rate of containment **(Fig. 4)**. This formulation resembles the "exposure index" for wildfires: the ratio of the total perimeter of a wildfire (in units of length) to the total production capacity of containment efforts (also in units of length), intended as a straightforward way to estimate the relative efficiency of firefighting resources and avoid unnecessary firefighter exposure (Calkin et al., 2011; Plucinski, 2019b). The potential for mechanistic coupling between intervention and hazard behaviours, represented as a probability distribution function, is likely greatest when $E \approx 1$ **(Fig. 4a)**. Characteristics of the intervention or hazard may change the shape of the probability distribution. For example, a particularly fast-moving event, like a flash flood, might squeeze the probability distribution into a narrow range of *E*; if the rate of hazard propagation is faster than any feasible intervention, the likelihood of mechanistic coupling might be near zero **(Fig. 4b)**. An intervention action that is only feasible under intervention-dominated conditions, such as for mechanical or safety reasons, might skew the likelihood of mechanistic coupling to the left; alternatively, an intervention action that is invoked only once a hazard event reaches a certain magnitude, perhaps because of high fixed costs, might skew the likelihood to the right **(Fig. 4c)**.

Like the exposure index or suppression-difficulty index for wildfires (Calkin et al., 2011; Rodríguez y Silva et al., 2014; Plucinski, 2019b), the utility of E might be at the planning stage for intervention operations: given the magnitude of an imminent or developing hazard event, and given the resources available for intervention, is counteraction likely to be effective at controlling the hazard, or will front-line operators be exposed unnecessarily? Should operators wade in, or wait it out?

Box 1: DOZER – a conceptual illustration

To illustrate the general principles of emergency landscaping, we consider DOZER (Lazarus, 2025, 2026): a deliberately simplified, agent-based, numerical model based on observations of emergency road crews (Lazarus & Goldstein, 2019), in which a bulldozer works to keep a beachfront road clear of sand during a storm (**Fig. 5**). In the model, sand washes onto the road through breaches in a fronting dune, prompting a bulldozer – the model agent – to plow it back. Natural and anthropic processes of sediment transport become mechanistically coupled in two ways. First, plowing alters patterns of sand deposition onto the road, which steers subsequent pulses of shallow overland flow and sand deposition, which compels further plowing. Second, if the bulldozer plugs a breach in the fronting dune, then the blocked storm flow is redistributed alongshore, exacerbating erosion of the dune at one or more neighbouring breaches. As it attempts to mitigate the impact of the storm, the bulldozer thus influences and responds to immediate and cumulative physical changes that spread across the model landscape.

Absent any reworking by the bulldozer, the model generates sand deposits with geometric characteristics and scaling relationships comparable to those measured in physical experiments and real settings (Lazarus, 2016; Lazarus et al., 2020, 2021, 2022). But plowing actions break those scaling relationships, driving a divergence in the states and behaviours of human-altered versus natural storm impacts. The human-altered landscape is quantitatively distinct from its natural counterpart.

What enables the bulldozer agent to respond to and interact with storm-driven deposition is that DOZER is, superficially, a single-player video game in which a player controls the bulldozer. The adaptive behaviour of the bulldozer agent in the model is handled directly by the player rather than evolutionary computation (Holland, 1995, 1998; Miller & Page, 2007). The bulldozer can perform only a limited set of actions (move, plow), yet they are sufficient to translate player decisions and strategies into a variety of model outcomes, even for the same initial conditions. Where the natural model of storm-driven sediment transport that underpins DOZER is deterministic, the adaptive dynamics introduced by the player-operated bulldozer shifts the human-altered coupled system into model states that are neither deterministic nor random.

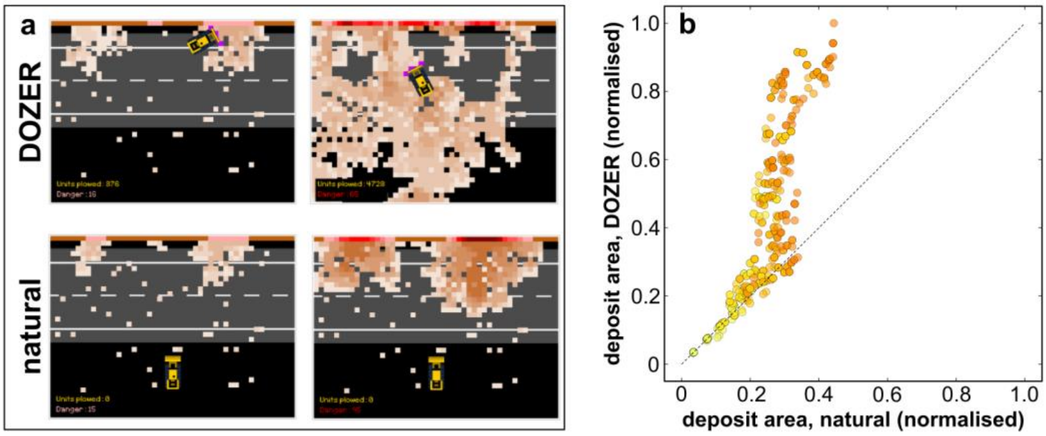

Figure 5. Numerical model DOZER as a conceptual illustration of emergency landscaping. (a) Screenshots of the human-altered (top) and natural (bottom) floodplain, as sand washes onto a beachfront roadway during a storm. Initially, the human-altered and natural conditions are similar (left), but diverge as the storm progresses (right). **(b)** Plotting total area of deposited sand for the human-altered versus natural conditions captures the divergence between the predicted result, in the absence of any intervention, and the observed result, which is a consequence of plowing by the player. The colour gradient (yellow to orange) darkens with elapsed time. Dashed 1:1 line represents perfect agreement between predicted and observed area of deposited sand.

5 Directions for future research

Consideration of emergency landscaping phenomena in natural hazard systems opens new avenues for intersectional research. I describe here a few possible directions.

5.1 Empirical signatures of interventions

Empirical comparison of how natural versus human-altered landscapes respond to hazard events is an essential step toward predicting future impacts (Nordstrom, 1994;

Haff, 2003). Characterising emergency landscaping as an anthropic force of physical environmental change will require quantifying and collating observations from a diverse catalogue of hazard cases. Rapid advances in the capture, resolution, availability, and analysis of remote-sensing data will generate new insight into patterns of environmental change, as will novel analytical machine-learning techniques for gleaning new information from archival remote-sensing data. These technological advances in observation can be leveraged to examine emergency landscaping interventions in spatial and temporal detail.

Even with the intensification of remote-sensing technologies, direct measurements of emergency landscaping actions may yield more immediate predictive gain than improved model physics or higher-resolution satellite imagery. Wildfire research continues to advance methods for directly measuring environmental conditions at a fire front, such as body sensors worn by wildfire fighters (Parker et al., 2017), which could help calibrate remotely sensed observations and integrate suppression actions into data-driven models of fire spreading (Plucinski, 2019a; Sullivan et al., 2020; Cheng et al., 2022). Similarly, tracking devices and sensor arrays could be attached to earth-moving vehicles in wildfire or coastal hazard settings. Such sensors are already applied in mining and automated-construction contexts (Fu et al., 2017; Jud et al., 2021).

Empirical approaches open questions such as: under what circumstances are physical indications of emergency landscaping discernible during or after a hazard event? Does emergency landscaping leave a quantifiable signature in the expression of the hazard footprint – its geometric or spectral characteristics, for example – that distinguishes human-altered impacts from natural ones? Over longer time scales, in places where emergency landscaping is recurrent, is any cumulative evidence of intervention embedded in how the setting changes over time?

5.2 Exploratory models

Empirical observations of emergency landscaping phenomena will motivate numerical modelling to explain those observations and probe their implications. Modelling can reveal potential system states and behaviours outside the directly observable, and frame testable hypotheses. Before hazard science can deliver spatially explicit simulation models for event prediction and operational decision-making, there are gains to be made from exploratory numerical models (Murray, 2007): heuristic tools for understanding how human-altered and natural landscape conditions may diverge during a hazard event. Like a glimpse into a parallel universe, a numerical model yields a complete record, in time and space, of both the human-altered event and its natural counterpart under the same forcing conditions, to enable an idealised quantitative comparison (Fujita et al., 2009; Scifone et al., 2010; Lazarus, 2026).

Forest fires motivated early forays into cellular-automata and agent-based modelling, in which the fire and trees were treated as agents (Bak et al., 1990). Nearly four decades later, in current agent-based models of wildfire spread, the principal agents still tend to be the fire and vegetation, not fire crews (Box, 2002; Miller & Page, 2007; Spyratos et al., 2007; Katan & Perez, 2021; Vigna et al., 2024: Hyun et al., 2025). There are numerous studies in wildfire science documenting field-scale tests of intervention methods (Plucinski, 2019a, 2019b), which an agent-based model could adapt to capture process coupling between a wildfire and fire suppression. Researchers also note the leap that separates a deliberately simplified physical model of wildfire spread from a model with operational applicability (Cruz et al., 2017). But outside of wildfires, intervention in other hazard systems is less examined. Numerical modelling of concurrent interventions in effusive volcanic eruptions, including water cooling (Fujita et al., 2009) or barrier construction (Scifoni et al., 2010), remains limited. Future modelling might take advantage of detailed reporting on diversion operations during the 1973 Eldfell eruption on Heimaey (Williams & Moore, 1976; Siguresirsson, 1997; Williams, 1997), or the 1991–1992 Mt. Etna eruption above Zafferana Etnea (Barberi et al., 1993). Laboratory models have advanced insight into the dynamics of lava flows (Lev & Rumpf, 2018), including their deliberate diversion with fixed structures (Dietterich et al., 2015); classic physical experiments that simulated lava flows with melted wax (Griffiths & Fink, 1992) could be adapted to incorporate water-cooling interventions. Exploratory numerical models involving storm impacts on low-lying coastlines have introduced bulldozer actions as a post-storm (Magliocca et al., 2011) or annual intervention (Anarde et al., 2024), but are not designed to address process coupling during a storm (Lazarus & Goldstein, 2019; Lazarus, 2026). Recent modelling has used an agent-based simulator to investigate local-scale interactions between people and rising floodwater at a shopping centre, including sandbag emplacement (Shirvani et al., 2021).

Where the modelling goal is to reveal system states, behaviours, and regimes, a model like DOZER (**Box 1**) demonstrates a simplifying advantage of using human (or machine) players to deliver the adaptive mechanics of an agent-based model, rather than generating them algorithmically (Holland, 1995, 1998; Miller & Page, 2007; Wilson et al., 2007). Inasmuch as a videogame constitutes a form of participatory model (Seidl, 2015; Schulze et al., 2017), a player-based design may open the model state space in ways inaccessible to, or otherwise inscrutable from, evolutionary computation techniques alone. Player-based participatory models could constrain the "computational irreducibility" of predictive hazard models by using player actions to map out potential outcomes that arise when natural and anthropic physical processes become mechanistically coupled (Levin, 2002; Beckage et al., 2011; San Miguel et al., 2012; Schlüter et al., 2012; Seidl, 2015; Schulze et al., 2017; Chattoe-Brown, 2023). Human players and a machine player (i.e., an evolutionary algorithm) could be tasked with a particular target for optimisation, and their approaches compared. For example, for

DOZER, a goal might be to achieve the longest run-time with the shortest-possible DOZER path length, or find the most mechanically efficient means of keeping the road clear of sand. Do human and machine players converge on the same solution? How might a hybrid machine-learning tool, trained on game data from human players, inform the performance of an autonomous landscaping vehicle (Jud et al., 2021)? With participatory modelling, even deliberately simplified models may deliver a distribution of outcomes that differs from the distributions arising from random, probabilistic, or machine-learning approaches. Quantifying any such comparative differences or similarities could be useful for next-generation hazard forecasting.

5.3 Strategy and decision science

Player-based participatory models could also help illuminate processes of decision-making from which individual or collective strategy emerges (Axelrod, 1997; Holland, 1995, 1998; Lansing, 2003; Miller & Page, 2007; Salen & Zimmerman, 2003; van Bilsen et al., 2010). For example, how do different individual players, and groups of players, engage with the same model condition, and what do their intervention actions collectively reveal about hazard impacts shaped by moment-to-moment decisions? Insights from player focus groups – comprising lay publics, hazard experts, field operators, or agency managers – could support strategy discussions among emergency planners. A multi-player model format could be used to examine the dynamics of cooperative strategies. Less realistic than simulators, such as those developed for wildfires (Neale & May, 2018, 2020; Symon et al., 2025), a multi-player interface for a deliberately simplified model might still capture a stylised version of the decision-making challenges that operators face in the field. Models of emergency landscaping phenomena would benefit from a closer understanding of how field operators perceive hazard situations (Hirsch et al., 1998), do the work required of them (Thomas, 2022), and make decisions under duress (Kowalski-Trakofler et al., 2003; Flin et al., 2017; Hoekstra & Montz, 2017; Reale et al., 2023) – not only to clarify mechanistic coupling but also to acknowledge the acute and cumulative psychological toll that event response may have on operators (Wagner et al., 2025). Longitudinal studies of management policy and operational approaches, from institutional and professional vantages, would help explain how a given type of emergency landscaping is implemented, how and why its implementation may have changed, and with what consequences for physical settings and people.

6 Conclusion

Emergency landscaping exemplifies a "peri-engineering" system: one that is neither fully natural nor fully engineered, "a region of reduced predictability and increased probability of malfunction or failure compared to the engineered system itself" (Haff, 2013). For a natural hazard event that triggers concurrent counteraction, reduced predictability of the hazard behaviour, and increased probability that an intervention might fail to exert control over the event, likely derives from the potential for hazard and intervention behaviours to become mechanistically coupled. This concurrent process coupling will tend to drive a divergence between predictions and observations of hazard impacts at the event scale.

If emergency landscaping interventions were not societally important, they would not be so prevalent and so integrated into emergency management. This ubiquity also means that in hazard-prone settings around the world, emergency landscaping phenomena are embedded in local environmental histories that entangle hazard exposure, infrastructure, hazard protection, and disaster events (Mileti, 1999; Jorgensen et al., 2013). Iterated over time scales of decades and longer, interventions that prevent frequent, minor hazard impacts may drive an environment toward a regime of infrequent, major hazard impacts – even without any increase in climate-driven forcing. In wildfire contexts, this feedback is termed the fire-suppression paradox (Krieder et al., 2024); in river contexts, it is characterised as flood enhancement through flood control (Criss and Shock, 2001; Werner and McNamara, 2007). An exacerbating feedback – termed the levee effect (White, 1945) or safe-development paradox (Burby, 2006) – can occur where defences to protect the built environment from hazard impacts unintentionally intensifies development within the hazard zone, such that failure of the protective infrastructure might have increasingly disastrous consequences (Werner & McNamara, 2007; Di Baldessari et al., 2013; Wenger, 2015; Armstrong et al., 2016; Armstrong & Lazarus, 2019). This antithetical relationship between hazard mitigation and impact escalation is a confounding dynamic in disaster risk reduction (Mileti, 1999), to which emergency landscaping contributes.

Emergency landscaping emerges as a common thread connecting otherwise disparate types of natural hazard, which suggests that methods for gaining physical and social insight into intervention actions may translate across research fields. In a given place, how have emergency landscaping practices changed over time? What are the environmental legacies of sustained intervention? What insights may come a more geographically distributed sampling of emergency landscaping? What other examples of emergency landscaping exist, current and historical? Systemic insight into the role of deliberate, concurrent, human interventions in natural hazard processes is critical to the endeavour shared across the hazard sciences to improve prediction and reduce disaster risk.

Conflict of Interest Disclosure

The author declares no competing interests.

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Open Research

Data and code used in this article are available at Lazarus (2026b). Code and model analytics for DOZER are available at Lazarus (2025).

Supplementary information

Photo credits for the images used in Fig. 1, and a detailed explanation of the data and methods used to generate the relationships shown in Fig. 2, are supplied in the Supplementary Information.

Figures & captions

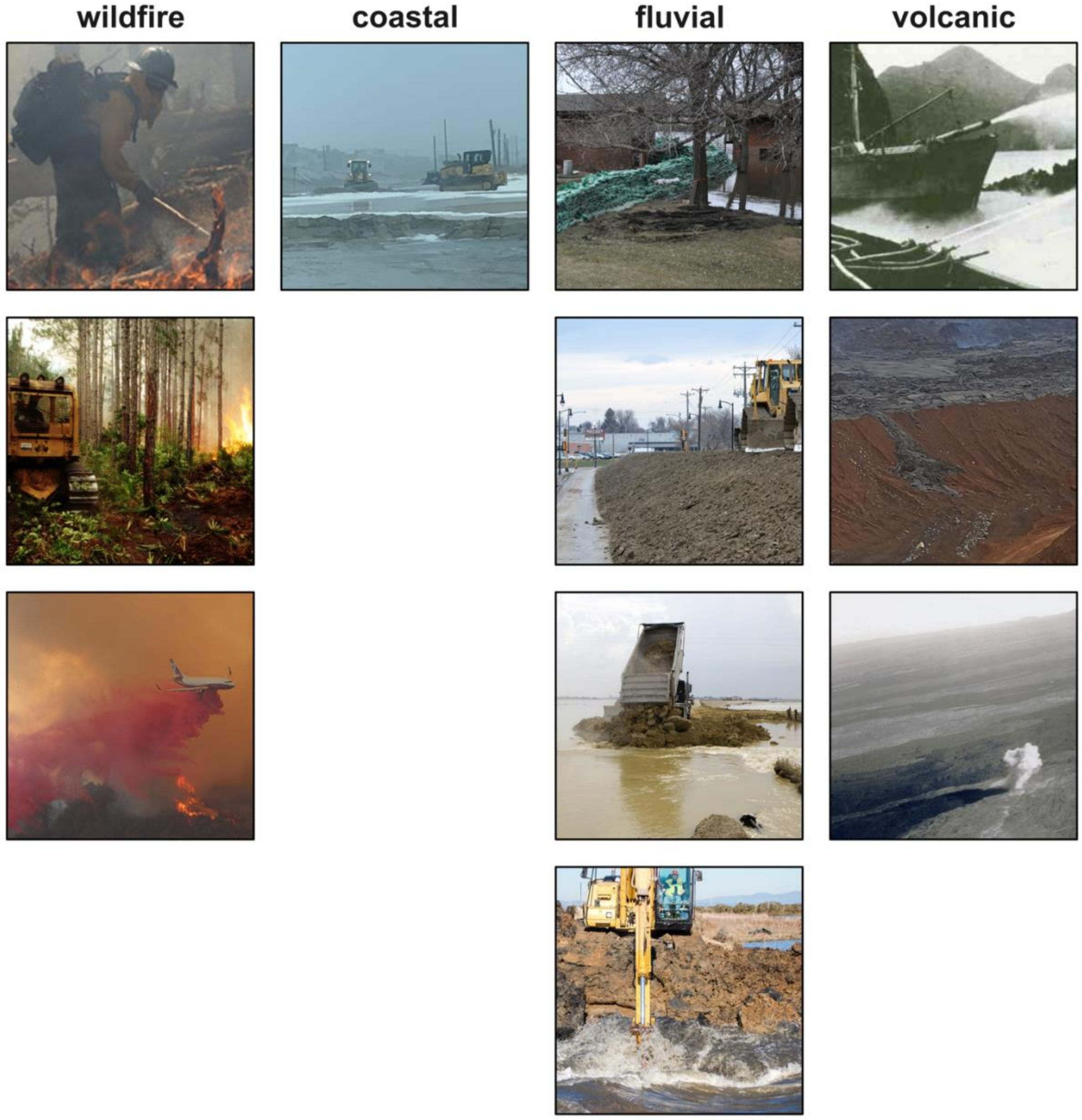

Figure 1. Examples of emergency landscaping. Deliberate, concurrent, mitigating interventions in the physical processes of natural hazard events occur in the context of wildfires, coastal storms, river flooding, and effusive volcanic eruptions. Wildfire interventions include fire suppression by handcrews, mechanised crews, and aircraft. Coastal interventions involve earth-moving vehicles that keep beachfront roads clear of sand during a storm event. Fluvial interventions include the construction of temporary levees with sandbags or earthen dikes, and closing or opening breaches in levees to control floodwater impoundment. Volcanic interventions to arrest or divert lava flows include water cooling, temporary earthen dams for flow containment, and aerial bombing or placed explosives. (All images in the public domain; image credits listed in **Table S1**.)

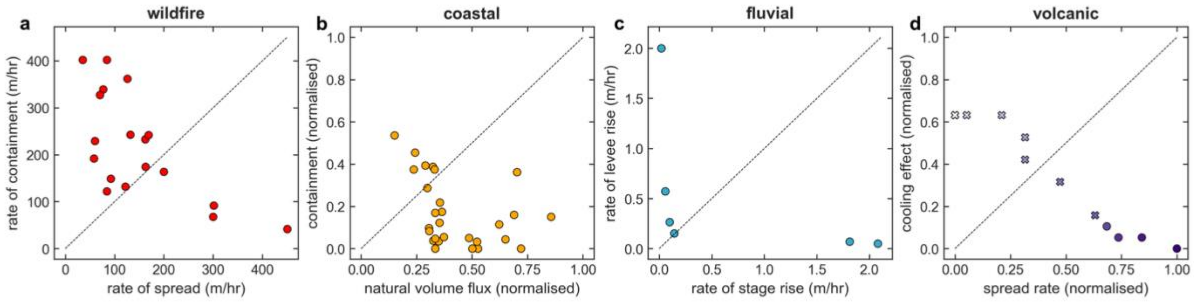

Figure 2. Inverse relationship between rates of containment and hazard propagation for four natural hazards. (a) Rate of wildfire containment by handcrews versus rate of wildfire spread, as reported in Hirsch & Martell (1996) and Murphy et al. (1991). **(b)** Sand containment versus natural sand flux, both normalised, in a simplified numerical model of emergency landscaping by a bulldozer during a coastal storm (Lazarus, 2025, 2026) (see **Box 1**). **(c)** Theoretical rate-of-rise for a sandbag levee in cross-section versus the mean daily average rate-of-rise of flood stages above bankfull at four UK river gages, along with reported rates-of-rise for a flash flood in one of the gaged rivers (Archer & Fowler, 2018). **(d)** Water-cooling containment versus lava spread rate, both normalised, from a numerical model of a single eruption on Izu-Oshima, Japan, by Fujita et al. (2009). Colour gradient (dark to light) indicates relative time. Circles indicate natural lava flow, prior to intervention; exes indicate flow altered by water cooling. Dashed diagonal line in each panel denotes 1:1 correspondence. Data sources and analytical methods are further described in the **Supporting Information**.

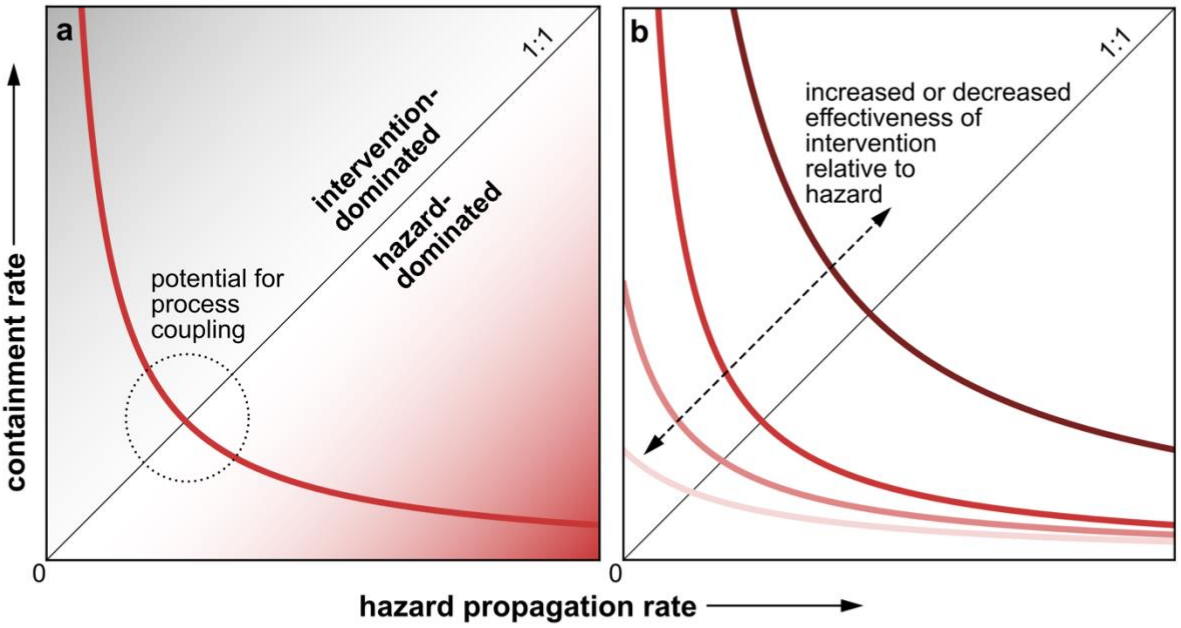

Figure 3. Theorised generic relationship between rates of containment and hazard propagation. (a) Where the rate of containment exceeds the rate of hazard propagation, the system state may be described as intervention-dominated; where the rate of hazard propagation exceeds the rate of containment, the system state is hazard-dominated. For a variety of natural hazard systems, the rates of containment and hazard propagation are inversely related; the curve shown (red) is based on the relationship described for wildfires (Hirsch & Martell, 1996). Physical processes of the intervention and hazard are most likely to become mechanistically coupled when the rates of containment and hazard propagation near parity. **(b)** The shape of the inverse relationship may change (e.g., shift, steepen, flatten) with increased or decreased effectiveness of the intervention relative to the hazard, even within the time frame of a single event.

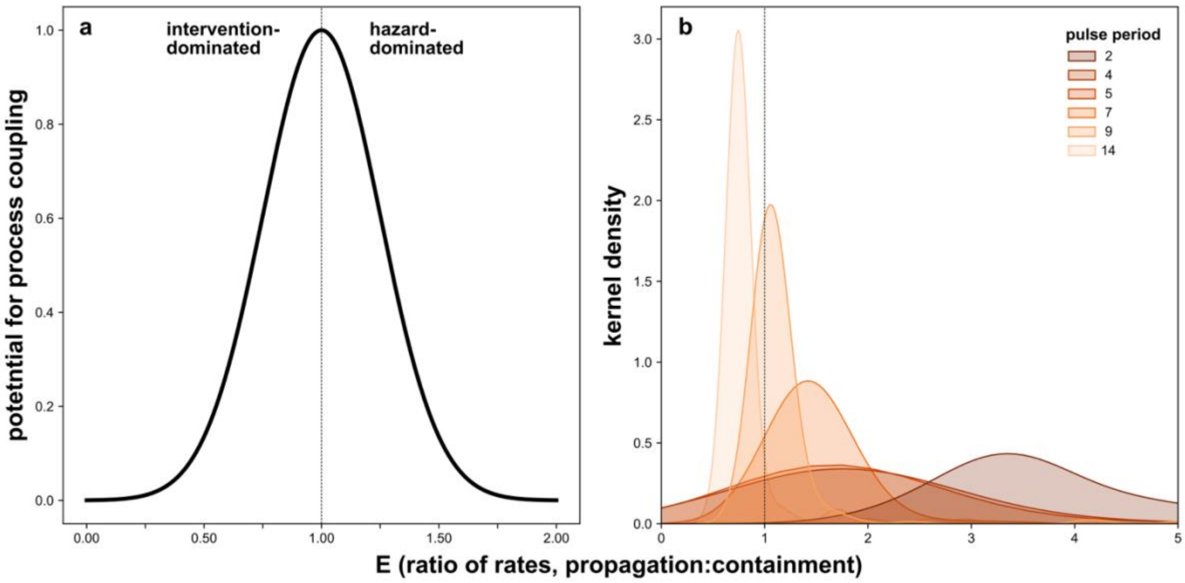

Figure 4. Theorised potential for process coupling as a function of *E*, or ratio of propagation and containment rates. (a) Physical processes of the intervention and hazard are most likely to become mechanistically coupled when the rates of containment and hazard propagation near parity. The dimensionless metric *E* is the ratio between the rates of hazard propagation and containment, respectively. When $E < 1$, the system state is intervention-dominated; when $E > 1$, the system state is hazard-dominated. The shape of the probability distribution of *E* may narrow or flatten if intervention actions are only effective, or marginally effective at best, within a narrow range of hazard propagation rates. Similarly, the probability distribution of *E* may skew right or left if interventions abruptly fail beyond a certain rate of hazard propagation, or if an intervention is only triggered by rates of hazard propagation above a certain threshold. **(b)** Kernel density estimate distributions of *E* for the modelled intervention into coastal storms shown in **Fig. 2b** (see also Box 1), where *E* is sampled at discrete timesteps during a each storm event. Distributions of *E* change with hazard intensity, where shorter pulse periods indicate stronger storm forcing. The region to the left of the vertical dashed line ($E = 1$) can be interpreted as intervention-dominated, and to the right as hazard-dominated.

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SUPPORTING INFORMATION

Control of natural hazard events through emergency landscaping

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Table S1. Image credits for Figure 1.

Image	Reference
wildfire (1)	Wildland firefighting. US Fire Service: https://www.fs.usda.gov/wildlandfire/
wildfire (2)	Bulldozer clearing a control line, Plantation Pines, Florida, USA, 26 June 1998. Liz Roll, FEMA https://commons.wikimedia.org/wiki/File:FEMA_-_832_-_Photograph_by_Liz_Roll_taken_on_06-26-1998_in_Florida.jpg
wildfire (3)	Air tanker drops fire retardant on the Fawn Fire near Redding, California, USA, 24 September, 2021. California Department of Forestry and Fire Protection: https://commons.wikimedia.org/wiki/File:Air_tanker_drops_retardant_on_Fawn_Fire_(2021)_near_Redding_CA.jpg
coastal (1)	Road-clearing crews working on NC Highway 12, Rodanthe, North Carolina, USA, 7 November 2021. North Carolina Department of Transportation: https://x.com/NCDOT_NC12/status/1457441243789733895
fluvial (1)	Sandbagging around homes along the Sheyenne River, Valley City, North Dakota, USA, 13 April 2009. Michael Raphael, FEMA: https://commons.wikimedia.org/wiki/File:FEMA_-_40653_-_Sand_Bag_Levee_in_a_North_Dakota_neighborhood.jpg
fluvial (2)	US Army Corps of Engineers constructing a temporary emergency levee in Fargo, North Dakota, USA, 29 April 2013. USACE/USDAgov: https://commons.wikimedia.org/wiki/File:The_U.S._Army_Corps_of_Engineers_(USACE)_completed_a_temporary_emergency_levee_near_the_city_hall_along_2nd_Street_in_Fargo,_ND,_Apr._29,_2013_(Pic_2).jpg
fluvial (3)	A truck dumps a load of rock into a levee breach in Oakville, Iowa, USA, 6 July 2008. Susie Shapira, FEMA: https://commons.wikimedia.org/wiki/File:FEMA_-_36988_-_Truck_dumps_rocks_into_a_levee_breach_in_Iowa.jpg

fluvial (4)	Cullinan Ranch levee breach, California, USA, January 2015. Steve Martarano, USFWS: https://commons.wikimedia.org/wiki/File:Cullinan_Ranch_Levee_Breach_(16048107267).jpg
volcanic (1)	Ship pumping seawater onto the forward margin of the Heimaey lava flow, March 1973. Sigurgeir Jónasson, courtesy of the USGS: https://commons.wikimedia.org/wiki/File:Ship_pumping_seawater_onto_the_forward_margin_of_the_Heimaey_lava_flow,.jpg
volcanic (2)	Earthen barriers at Stóri Hrútur, Iceland, May 2021. Berserkur: https://commons.wikimedia.org/wiki/File:St%C3%B3ri_Hr%C3%BAtur.jpg
volcanic (3)	Aerial view of a bomb detonating on Mauna Loa near the source of the 1935 Humuʻula lava flow, 27 December 1935. Army Air Corps (via USGS): https://www.usgs.gov/media/images/old-bombs-found-mauna-loa-rest-story-part-2

Regarding data and analytics in Figure 2 (main text)

The data and code used to recreate the plots in Fig. 2 of the main text are available at Lazarus (2026b).

Wildfire (Fig. 2a)

These data for wildfire containment versus spread rates are reported in Hirsch & Martell (1996: Fig. 2), after from Murphy et al. (1991). Data points in the plot by Hirsch & Martell (1996) were recovered using the WebPlotDigitiser tool (https://automeris.io/), and converted into equivalent units (m/hr).

Coastal (Fig. 2b)

These model results were generated from 28 model runs of DOZER (Lazarus, 2025) for different forcing periods of washover pulses. Forcing periods ranged from 2 seconds (representing a more intense storm) to 14 seconds (for a less intense storm), and did not vary within a given model run. The capacity of the bulldozer (speed, blade volume) and all other initial conditions for the model domain (e.g., dune height) were held constant.

DOZER tracks two versions of each run: the "human-altered" version generated by the user, and a deterministic "natural" version that returns the washover deposition that would have occurred in the absence of any intervention. The representative sand flux for the human-altered and natural version of each run is the mean of the sand volume on the floodplain divided by run time, taken at each model time step. Containment is calculated as the difference between the natural and human-altered volume fluxes at each time step, relative to the natural volume flux at that time step. High containment means that the human-altered volume flux is low, because the bulldozer manages to keep the floodplain largely clear of sand. Mean natural volume flux is normalised by the maximum mean volume flux among the 28 model runs.

Relative containment in DOZER reflects a nonlinear relationship between intervention and hazard rates similar to that seen in wildfires (**Fig. 2a**, main text). Direct comparison of DOZER versus natural volume fluxes returns an essentially flat curve (**Fig. S1**). This is because, unlike, for example, wildfire crews who fatigue faster as wildfire intensity increases, the plowing capacity of the model bulldozer does not change with storm intensity. As long as there is sufficient sand on the floodplain, the bulldozer is always able to plow at a rate approximate to its maximum, which is a fixed parameter. In reality, plowing capacity would likely decrease as washover volume increases, as more sediment-laden water flushes around the vehicle.

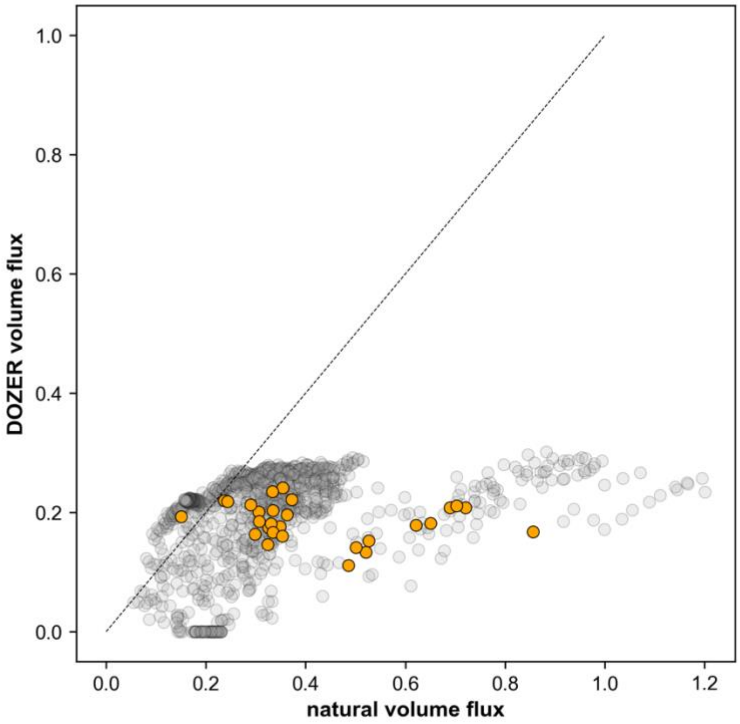

Figure S1. Comparative fluxes of sand volume in DOZER. Grey circles record the relative fluxes at each model time step; orange circles show the mean DOZER and natural volume fluxes for each run. Dashed reference line represents 1:1 correspondence. Natural volume flux reflects a range of forcing periods between 2 seconds (representing a more intense storm) and 14 seconds (for a less intense storm); forcing period does not vary within a given model run. The ratio of natural to DOZER volume fluxes, derived from the grey circles, is used to calculate distributions of the metric *E*, shown in **Fig. 4b** (main text.)

Fluvial (Fig. 2c)

The underlying data for daily average rate-of-rise (m/hr) are available from the UK National River Flow Archive, maintained by the UK Centre for Ecology and Hydrology. Data regarding a specific flash-flood event on the rivers South Tyne and Tyne, in northern England, were reported by Archer & Fowler (2018; Table 2).

Gaging station // site	**Reference**
53018 – Avon at Bathford	https://nrfa.ceh.ac.uk/data/station/peakflow/53018#rating
55023 - Wye at Redbrook	https://nrfa.ceh.ac.uk/data/station/peakflow/55023#rating
23009 - South Tyne at Alston	https://nrfa.ceh.ac.uk/data/station/peakflow/23009#rating
23004 – South Tyne at Haydon Bridge	https://nrfa.ceh.ac.uk/data/station/peakflow/23004#rating
23001 - Tyne at Bywell	https://nrfa.ceh.ac.uk/data/station/peakflow/23001#rating
Alston, Featherstone, Haydon Bridge, Bywell	1-hr maximum rise, reported by Archer & Fowler (2018: Table 2)

This is an illustrative sample, not a systematic sample from the National River Flow Archive dataset. Not all stations in the archive record peak flow data or have associated rating curves; stations that do might not necessarily record flood stages. The Avon and Wye gages used here were chosen because they are on river reaches known to flood, and had sufficiently long records from which to calculate a large number of flood stage rates-of-rise. The Tyne gages were chosen because they correspond to reporting by Archer & Fowler (2018) on a flash-flood event in 2002.

Daily discharge measurements (m^3/s) were converted to stage (m) with rating curves for each station. Daily average rates-of-rise (m/hr) are taken as the difference in stage on successive days, divided by 24 hours. Negative changes were discarded, as were any stages below bankfull for that station.

Daily average rates-of-rise above bankfull were binned relative to estimated rates-of-rise for a sandbag levee in cross-section. Practical guidance from the UK Environment Agency (2009) suggests that a two-person team can prepare, on average, 12 sandbags per hour. Separate guidance from the US Army Corps of Engineers (2022) for the construction of sandbag levees indicates that the number of sandbags required to complete a stable levee (i.e., pyramid construction) increases quadratically with flood stage height. Combining these terms yields a relationship for estimated sandbag levee rate-of-rise as a function of flood stage rate-of-rise (**Fig. S2**).

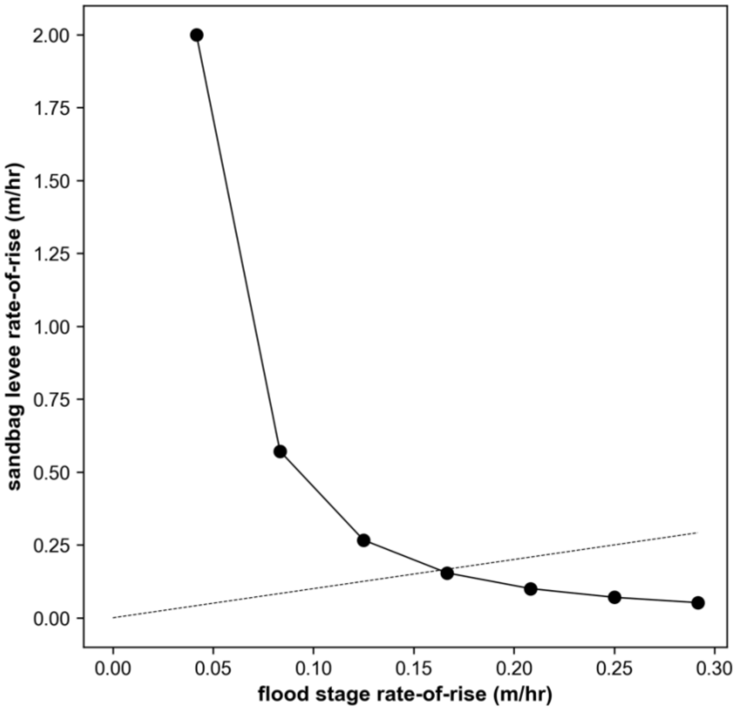

Figure S2. Relationship for estimated sandbag levee rate-of-rise as a function of flood stage rate-of-rise. Curve assumes a two-person team filling sandbags at a rate of 12 sandbags per hour (EA, 2009), and a sandbag levee at a single cross-section (USACE, 2022). Dashed reference line shows 1:1 correspondence.

In the absence of direct measurements from field examples, daily average rates-of-rise from the gage data were binned to the nearest sandbag levee rate-of-rise to which they are less than or equal (**Fig. S3**). The data suggest that most daily average rates-of-rise for flood stages at these gaging stations are slower than associated rates-of-rise for construction of a sandbag levee (**Fig. S3a**). However, rates-of-rise associated with a flash flood on the South Tyne and Tyne (Archer & Fowler, 2018) show how the shape of the emergency landscaping curve changes with the inclusion of a truly extreme event for these selected rivers (**Fig. S3b**).

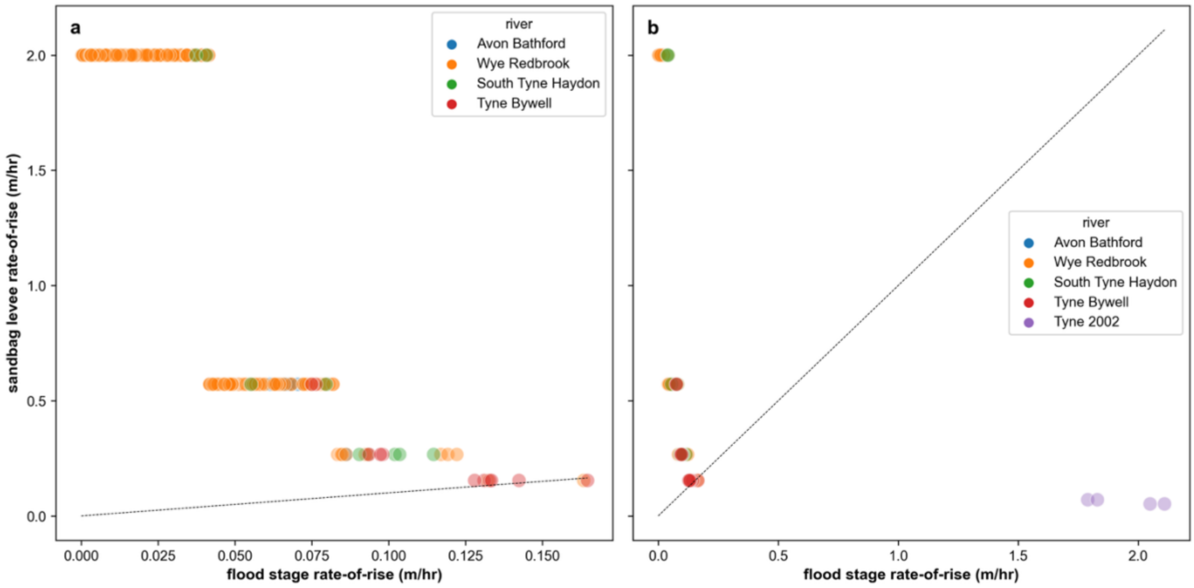

Figure S3. Estimated sandbag levee rate-of-rise as a function of flood stage rate-of-rise for gaged and reported data. Following **Fig. S2**, this relationship assumes a two-person team filling sandbags at a rate of 12 sandbags per hour (EA, 2009), and a sandbag levee at a single cross-section (USACE, 2022). **(a)** Flood stage rates-of-rise for gaged data. **(b)** Flood stage rates-of-rise for gaged data and flash flood rates-of-rise reported by Archer & Fowler (2018). Means of these binned data are shown in **Fig. 2c** (main text). Dashed reference lines show 1:1 correspondence.

Volcanic (Fig. 2d)

Modelled time series for relative area inundated by an effusive lava flow on Izu-Oshima, Japan, under natural conditions and in response to a point-source water-cooling intervention, respectively, are reported in Fujita et al. (2009: Fig. 2). Discrete points in the plotted time series (natural and water-cooled) were sampled at a regular interval using the WebPlotDigitiser tool (https://automeris.io/). Sequential rates of spread for the natural case were calculated by taking the difference in inundated area between successive time steps and dividing by the step interval. As the flow cools with distance from the vent, the rate of spread naturally slows to zero. The estimated effect of the water-cooling intervention is calculated by subtracting the difference in inundated area for the natural and water-cooled cases at each time step, divided by the step interval. Upslope of the point-source intervention, the water-cooling effect is zero. Downstream, the effect becomes evident: increasing as the flow slows down, and stabilizing once the flow stops. This trajectory captures the behaviour of a single flow event, rather than the direct effect of water-cooling on a range of lava flow rates. The model data nonetheless reflect a nonlinear relationship between containment and hazard rates within an event.

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