

Human amplification of secondary earthquake hazards

Emma M. Hill^{†1,2}, Jamie W. McCaughey³, Adam D. Switzer^{1,2}, David Lallemand^{1,2}, Yu Wang⁴ and Sharadha Sathiakumar¹

1. Earth Observatory of Singapore, Nanyang Technological University, Singapore, Singapore
2. Asian School of the Environment, Nanyang Technological University, Singapore, Singapore
3. Department of Environmental Systems Science, ETH Zürich, Zürich, Switzerland
4. Department of Geosciences, National Taiwan University, Taipei, Taiwan

[†]e-mail: ehill@ntu.edu.sg

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Abstract

Anthropogenic climate change and modification of landscapes--such as deforestation, sediment movement, irrigation and sea-level rise--can destabilise natural systems and amplify hazards from earthquake-triggered landslides, liquefaction, tsunami, and coastal flooding. In this Review, we examine the connections and feedbacks between human environmental modifications and secondary earthquake hazards to identify steps for hazard mitigation. Destabilization of slopes by vegetation removal, agricultural activities, steepening, loading, and drainage disruption can amplify landslide hazards. For example, landslides were mainly triggered on deforested slopes after the 2010 and 2021 Haiti earthquakes. Liquefaction hazards are intensified by extensive irrigation and land reclamation, as exemplified by liquefaction causing >15 m displacement in irrigated areas after the 2018 Palu earthquake. Degradation or removal of primary coastal vegetation and coral reefs, destruction of sand dunes, subsidence from groundwater withdrawal, and sea-level rise can increase tsunami inland reach. Restoration of natural coastal habitats could help decrease the maximum inland reach of tsunami, but their effectiveness depends on tsunami size. Sustainable farming practices, such as mixed crop cultivation and drip irrigation, can successfully reduce the saturation of soils and the liquefaction hazard in some situations. Future research should explore the potential of such sustainable practices and nature-based solutions in reducing earthquake-related hazards, in addition to their climate and ecosystem benefits.

Website Summary:

Human modifications to the environment can amplify the secondary impacts of earthquakes, such as landslides, liquefaction, and tsunamis. This Review explores the relationships between environmental modification, sea-level rise, and earthquake-triggered hazards to identify potential solutions for hazard mitigation.

Key points

1. Human modification of the environment, both at a local and global scale, can amplify the secondary hazards of earthquakes, such as landslides, liquefaction, and tsunami. Understanding the history of landscape modification is helpful to understanding hazard drivers and could thus contribute to future mitigation solutions.
2. Direct human influences on secondary earthquake hazards include vegetation removal, sediment movement, slope modification, and hydrological disturbance. Indirect human influences include the impacts of climate change, such as increasing temperatures, extreme weather, and sea-level rise.
3. Saturated soils from irrigation and/or deforestation practices can reduce the stability of hillslopes and increase the risks of landslide and liquefaction hazards. Mixed crop cultivation and drip irrigation techniques reduce the saturation of soils and therefore could reduce the liquefaction hazard in some situations, while also reducing water use and greenhouse gas emissions.
4. Restoring natural coastal ecosystems and habitats with sand dunes, beaches, mangrove forests and seagrass meadows, can provide some protection against tsunami, but there are limitations to their mitigation potential for moderate to large tsunamis over a few metres high.
5. Even though biodiverse coastal ecosystems do not provide full protection against tsunami, their potential for limited hazard reduction along with a host of other ecosystem services and

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carbon sequestration benefits should be an argument for preserving and restoring them as much as possible.

6. Future research should prioritize exploring the co-benefits of sustainable practices in restoring and stabilizing landscapes so they are less susceptible to failure during earthquakes.

[H1] Introduction

Earthquakes and their cascading hazards result in some of the most devastating disasters on Earth, often resulting in regions of severe damage over several hundreds of kilometres. For the 100 deadliest earthquakes since 1900, secondary hazards such as landslides, liquefaction, and tsunami are estimated to have caused ~40% of economic losses and fatalities, with the rest attributed to primary effects from ground shaking¹. While careful engineering can often protect buildings and infrastructure against seismic shaking, few structures can withstand a major landslide. For example, the 2004 Indian Ocean earthquake triggered a tsunami that caused an estimated 227,898 deaths over 14 countries^{2,3}, making it one of the deadliest events in modern history. A large fraction of the ~ \$200 billion in economic loss resulting from the 2011 Tohoku-Oki (Japan) earthquake has been attributed to the tsunami⁴. Liquefaction triggered by the 2010-2011 Christchurch earthquake sequence (New Zealand) caused ~\$10 billion in economic damage¹. As such, the term 'secondary earthquake hazards' is used in this Review to indicate that the hazard was geophysically triggered by an earthquake, not to indicate the relative severity.

Human modification of the environment can substantially increase the hazard potential of a region, including the impacts of earthquakes. Humans have modified about three-quarters of the Earth's land surface within the last thousand years⁵, as such the scale and magnitude of alterations are much greater than natural or geological processes⁶. Environment-modifying activities include urbanisation and construction of infrastructure (both on the surface and in the subsurface), mining, movement of sediment, land reclamation, vegetation removal and change (including the introduction of cultivation), fire (both deliberate to clear land and accidental wildfires), groundwater extraction, fluid injection, drainage and dewatering of soils, re-routing of rivers and reservoir construction^{7,8}. For example, construction of roads and deforestation in hilly terrains can increase the number of earthquake-triggered landslides⁹⁻¹², modifications to the water table from irrigation can result in earthquake liquefaction where soils would otherwise remain compact^{13,14}, and removal of mangroves can remove a layer of protection from tsunami^{15,16}. At a global level, anthropogenic carbon emissions have resulted in ongoing climate change¹⁷, with ongoing impacts such as global temperature increase, increase in extreme weather events and sea-level rise. For example, forest fires or abandonment of agricultural land on slopes due to rising temperatures can weaken slopes and result in higher landslide hazard^{18,19}, while sea-level rise can increase tsunami and liquefaction hazard along coasts²⁰. In many countries worldwide the history of land use is intimately connected with colonial history and its modern repercussions, as colonization caused and continues to impact ecological catastrophes and rapid deforestation²¹ (Box 1 and Box 2).

In this Review, we explore how human modification of the environment can have unintended consequences on the occurrence and/or impact of secondary earthquake hazards (Table 1). We focus on secondary earthquake hazards, such as landslides, liquefaction and tsunami, rather than ground shaking or induced earthquakes. The focus of this Review is on the unintended consequences of environmental change on the amplification of earthquake hazards, and as such, the purposeful human engineering solutions in reducing these hazards (for example, through the construction of seawalls)²², are not in scope. In addition, as the focus is on the geophysical secondary hazards themselves, we do not focus on social drivers of vulnerability and exposure (such as economic inequality and political and social marginalisation) — which are the primary drivers of risk — nor on cascading or indirect impacts (such as disruptions of supply chains, outbreaks of disease, or intergenerational socio-economic consequences). We touch on the topics of exposure and vulnerability only in the detailed case studies (Box 1 and Box 2), where we aim to discuss two disasters with a more holistic approach.

However, we acknowledge that a holistic understanding of risk can only be achieved through examination of both social and environmental drivers²³, and we suggest that such joint assessments should be a priority for further research.

[H1] Compounding earthquake-induced landslides

Landslides are defined by the movement of soil or rock downslope when gravitational forces exceed the frictional resistance of the surface material. Earthquake shaking can act as a landslide-trigger on unstable slopes, resulting in considerable damage to affected areas and often causing interruptions to regional lifelines such as transportation, energy, and communications infrastructure. In this section, we discuss mechanisms by which human modification of environment and climate can impact landslide hazard from earthquakes. Note, liquefaction-induced lateral spreading (termed ‘flowslides’), which can occur on gentle or previously stable slopes, are discussed in the next section.

[H2] Slope destabilization

Anthropogenic modification of the environment is recognized to have had a key role in amplifying landslide hazard for many areas. However, landslides are polycasual phenomena, and human influences can rarely be fully separated from natural ones²⁴. Humans can influence slope stability by a variety of local processes such as removal of vegetation, agricultural activities, steepening or loading of the slope, introduction of road cuts, and disruption of drainage. Slope stability can also be impacted by global anthropogenic processes like climate change, which is resulting in changes in surface temperature, increased likelihood of forest fires, changes in precipitation patterns, and extreme storms^{24,25} (Figure 1).

[H2] Earthquake-related landslides

General factors influencing the propensity for earthquake-triggered landslides include the earthquake magnitude, distance of the epicentre, focal depth, direction of seismic wave propagation, seismic wave attenuation, and the stability of the slope^{9,26,27}. In contrast to rain-induced landslides, earthquake-induced landslides tend to occur in convex topography, which can amplify seismic waves²⁸. Relationships between earthquake magnitude, peak ground motions, and landslide frequency and distance from the epicentre have been developed based on large catalogues of earthquake-triggered landslides^{27,29-31}, but outliers can be the result of human-caused slope instability (or anomalous seismic attenuation)²⁹. These outliers show that human modification of the environment can increase the spatial extent of the area that experiences landslides and/or cause failures at lower shaking intensities.

Earthquakes can have long-lasting influences on slope stability, meaning that both the history of the landscape and the legacy of past earthquakes should be considered in landslide hazard models³². Landslides peak at the time of the mainshock then occur with a slow decay in frequency over the subsequent years³³. Cracks and holes produced by an earthquake can both weaken the slope and boost seismic shaking in future earthquakes³⁴. Earthquakes can also result in increased frequency of rain-induced landslides, for example, the rate of rainfall-triggered landslides increased by 22 times in Taiwan after the 1999 M_w 7.6 Chi-Chi earthquake, taking up to four years to return to pre-quake levels³⁵. So while there might be differences between earthquake-induced and rain-induced landslides (for example, in the vulnerability of convex versus concave slopes), examples based on rain-induced landslides remain relevant to this review.

[H2] Land use change

Land cover is one of the most important influences on slope stability. Deforestation of slopes, often for conversion to agricultural cultivation or pasture, has increased landslide hazard in many parts of the world due to reductions in vegetation rooting strength and modification of hydrological processes⁹ (Figure 1). This deforestation happened hundreds to thousands of years ago in some cases, leaving a long-term legacy of risk modification. However, while forests are generally understood to stabilise slopes, in some cases they can increase water infiltration and thus reduce stability²⁵.

New Zealand provides a useful case study for scientific analysis of the impact of land-cover change because the history of the change is relatively short. Deforestation in New Zealand occurred primarily over the 13th to mid-20th centuries, with primary growth forest reduced over this time from ~82% to ~23% of total land area³⁶, and a corresponding decrease in slope stability compared to prehistoric conditions^{37,38}. A comparison of the locations and characteristics of rockfall boulders dislodged during the 2010-2011 Canterbury earthquake sequence (of which there were >7000 mapped individual rocks) with those from earthquakes that occurred prior to human settlement shows that the modern rockfalls travelled 100-250 m further than the prehistoric events³⁹. The prehistoric distances can be explained by incorporating a native forest into numerical landslide simulations³⁹. Another case study highlighting the link between deforestation and slope stability is provided by the 2010 and 2021 Haiti earthquakes (Box 1).

A particularly detrimental land-cover change is abandonment of cultivated land. Deforested land with no land or water management represents the land-cover type most susceptible to shallow landslides¹⁸. Areas of the Italian Alps and Apennines have seen increased numbers of landslides in areas of abandoned vineyards and olive groves^{18,19}, where unhealthy plants and poorly maintained human structures can weaken stability and suffer drainage problems. This abandonment of cultivated land is likely to have increased the susceptibility of earthquake-induced landslides in the area but has not been closely investigated.

As land cover is dynamic, landslide hazards should never be considered static. Additionally, changes in land cover can – in a feedback process – be a consequence of earthquake and landslide activity. For example, landslides in farmed areas can result in land abandonment^{18,40}, which in turn could amplify landslide hazard.

[H2] Construction and roads

Construction of mountain roads has been demonstrated to substantially increase landslide occurrence by undercutting slopes, loading and steepening slopes, and modifying drainage patterns⁹⁻¹² (Figure 1). The highest risk is unimproved and poorly engineered roads which lack proper design for stability and drainage¹¹.

As an example, the 2005 M_w 7.6 Kashmir earthquake triggered thousands of landslides over an area of >7500 km², and 53% of these landslides were in areas modified by anthropogenic activities⁴¹.

Proximity to roads was a primary influence, with slope failure occurring along nearly every stretch of road occupying slopes steeper than 50°⁴¹. Another example is the 1999 M_w 7.6 Chi-Chi earthquake in Taiwan, where landslides occurred over a ~28-km-long stretch of the central cross-island highway⁴². Over two decades after the earthquake, this part of the highway is not yet fully reopened. Both these examples illustrate the amplification of impacts, as roads can contribute to the occurrence of landslides. In addition, the destruction or blockage of roads by landslide activity can compound the impacts of the earthquake by cutting off access and aid lifelines.

[H2] Climate change and landslides

The IPCC concludes that increases in temperature, precipitation, and rainfall intensity are “likely” or “very likely” a result of human-induced climate change¹⁷. All these climate parameters have and will continue to influence slope stability and probability of landslide triggering, including earthquake-triggered landslides⁴³ (Figure 1). The impact of weather and climate on landslides is already illustrated by seasonal modulation of landslides worldwide⁴⁴. Confirming the potential for future increases in hazard, the IPCC states that there is “high confidence” that changes in heat waves, glacial retreat, and/or permafrost degradation will affect slope instabilities in high mountains, and “medium confidence” that temperature-related changes will influence bedrock stability⁴⁵. Increases in extreme precipitation will also amplify hazards⁴⁶. The incorporation of climate change scenarios into predictions of landslide hazard, however, is complex and hampered by a lack of resolution in the climate predictions^{9,25}. Landslide hazard forecasts need to include not only the direct effects of changes in weather and climate, but also their impacts on ecosystems and the vegetation that can help to stabilise slopes. For example, increased temperatures will see increased likelihood of forest fires (there has been an estimated 18.7% increase in global mean fire season length over the period 1979 to 2013⁴⁷), which can remove vegetation, damage soil, and modify the water absorption properties of the soil, thus modulating landslide hazard.

While it can be inferred that climate change will increase the number of landslides triggered by earthquakes (in particular, perhaps, by modifying the rate of decay of landslide occurrence after the main event³³), most of the published studies on landslides and climate change are based on rainfall-induced landslides. Additional research is needed to assess relations between climate change and earthquake-induced landslides.

[H1] Compounding soil liquefaction

Soil liquefaction--defined as the loss of strength and cohesion of water-saturated sediments in response to shaking--is a frequent occurrence in earthquakes, being reported for ~62% of large earthquake events²⁶. Liquefaction can result in the collapse or tilting of buildings and infrastructure as foundations settle and the soil cannot support the weight of the building, or displacement and damage by lateral spreading (often termed ‘flowslides’, the lateral motion of soil deposits on gently to steeply dipping slopes occurring due to liquefaction). Local human influences on liquefaction include land reclamation and water table rise through disruption of hydrological systems (Figure 2). In terms of global influences, sea-level rise can also raise the water table of coastal cities, thus increasing liquefaction hazard.

[H2] Land reclamation

Liquefaction is common in areas of reclaimed land in coastal areas, in areas of poorly compacted fill, and in alluvial deposits that include former riverbeds and water bodies²⁶. These landscape types are also particularly susceptible to elevated levels of seismic shaking.

The 2010-2011 Canterbury earthquake sequence in New Zealand illustrates the importance of understanding the history of environmental change. These earthquakes triggered widespread liquefaction and irreparable damage to ~15,000 houses in the Christchurch region⁴⁸⁻⁵⁰, in a pattern that reflected the prior history and landscape modification of the region. Prior to European settlement in 1850, Christchurch and neighbouring Kaiapoi was dominated by wet, marshy swamps, sand dunes and meandering streams and rivers^{48,51,52}. These swamps were drained during European settlement, and since then the fluvial systems have been extensively modified and many former river channels and low-lying areas have been raised with artificial fill, leaving present-day conditions of loose silt,

sand and gravel and a shallow water table⁵³. During the Canterbury earthquake sequence, areas of strong liquefaction correlated with the locations of former river channels that had been raised with artificial fill and then developed^{48,52} (Figure 2).

The importance of understanding the location of former river channels was also demonstrated in the Tokyo Bay region during the 2011 M_w 9.0 Tohoku-oki earthquake, Japan. Widespread liquefaction and lateral spreading in the Tone River catchment area resulted in a total of 920 levee failures in the Kanto plains, along with damage to buildings and infrastructure⁵⁴, predominantly on poorly compacted fills and former swamps and river channels. The level of damage might seem surprising given that the distance of the epicentre was over 300 km away and that the shaking was correspondingly moderate, but the damage reflects a history of major fluvial modification to the Tone River that started in the 17th century and continued for 400 years⁵⁴. These modifications have been so extensive that the location, tributaries and watershed of the Tone River are mostly man-made, and it now flows eastward into the Pacific Ocean instead of southward into Tokyo Bay.

The 1989 M_w 6.9 Loma Prieta earthquake, San Francisco, USA, is yet another example of liquefaction occurring in areas of extensive human modification. Large areas of the city are built over marshlands and dune sands, or reclaimed land in coastal zones, and these liquefied during the earthquake⁵⁵. These areas had also been documented as having liquefied in the 1906 San Francisco earthquake⁵⁵.

As an aside, although we do not focus on ground shaking in this Review, it is important to note that ground shaking is also intensified in areas of reclaimed land. Mexico City, built on a former lakebed, illustrates this concept. Seismic waves are trapped and amplified by the underlying lake sediments under Mexico City, resulting in strong ground shaking and extensive damage, as witnessed both in both the 1985 M_w 8.0 and 2017 M_w 7.1 earthquakes^{56,57}. The history of Mexico City also illustrates the potential for historical decisions to influence earthquake risk over century-long periods. Mexico City was built by Spanish colonisers following their conquest and destruction of the Aztec capital Tenochtitlan in 1521⁵⁸. The Aztec city had been built on two small islands in the marshes of Lake Texcoco, which the Aztecs expanded using small artificial islands. The Spanish then gradually drained Lake Texcoco in the area that is now the location of present-day Mexico City. This historical case has implications for development decisions where climate change and water use result in shrinking of inland water bodies, such as the Great Salt Lake (USA) and Aral Sea (Central Asia). Particularly where receding lakes are immediately adjacent to expanding urban areas, the planning of new developments should account for amplification of seismic hazard in lake sediments.

The examples in this section make a compelling case for accurately mapping the locations of paleochannels, former water bodies and reclaimed land under buildings and infrastructure in any earthquake-prone region. Analysis of historic land-use change is a key step towards assessing liquefaction hazard for any populated area.

[H2] Elevation of the water table

Elevation of the water table has important implications for liquefaction, for which even small increases in the water table can amplify hazard²⁰. When the groundwater table rises, it reduces the soil's effective stress and increases pore water pressure, weakening the soil and raising the risk of liquefaction in the area. Coastal areas are highly susceptible to changes in water table levels due to their immediate vicinity to the sea. The local geology also influences water table fluctuations, with more permeable soils allowing for better water seepage and an increase in water table elevation. Human activities such as groundwater extraction and irrigation can locally alter water table levels. Rising sea levels and climate change-induced extreme weather events, like storm surges, can also

increase water table levels in coastal aquifers, potentially leading to saltwater intrusion and exacerbating liquefaction risks.

In coastal areas with unconfined aquifers, the water table will increase with sea-level rise just as it is known to adjust to tides and ocean fluctuations. Relative sea-level rise will expand the areas susceptible to liquefaction. In case studies for Christchurch (New Zealand) and Yokohama City (Japan) the expansion of the liquefiable area with relative sea-level rise is substantial^{59,60}. For example, relative sea-level rise of 0.5 m in the Christchurch region is predicted to raise the groundwater level by the same amount to a distance of at least 2 km from the coast⁶⁰, increasing the area prone to liquefaction during an earthquake.

The introduction of irrigation systems for agriculture in a region can also modify soil saturation and the height of the water table. Irrigation can thus introduce liquefaction hazard to otherwise stable areas, including on near-horizontal slopes. Extensive lateral spreading (or “flowslides”) associated with the 2018 M_w 7.5 Palu earthquake, Indonesia, provides a worrying example of this hazard ([Box 2](#)). Another specific example is the observation of severe liquefaction at irrigated rice fields during the relatively low magnitude 2018 M 5.7 Songyuan earthquake, China, with neighbouring dry areas experiencing relatively low levels of liquefaction⁶¹.

Over 60% of the world’s irrigated area is in Asia, with much of this irrigated area dedicated to wet rice cultivation⁶². While traditional wet-rice farming has been practiced for millennia, the irrigated area has increased dramatically through the construction of aqueducts, canals, dams, and exploitation of groundwater, now covering an area of ~190 million ha across Asia⁶². In South and Southeast Asia, many of these systems were developed by colonial powers in the 19th to 20th centuries, with a rapid expansion also occurring in the period 1960 to 2000⁶². While these systems have greatly expanded food production, they could also contribute to greater liquefaction hazard during earthquakes.

In some countries, irrigation has a long history. For example, the Dujiangyan irrigation system in Sichuan, China, was constructed in ~256 BC and still irrigates an area of >673,000 ha⁶³. There was extensive liquefaction in the Dujiangyan catchment as a result of the 2008 M_w 7.9 Wenchuan earthquake, with some of this liquefaction occurring on irrigated rice fields⁶⁴. For this Review, we were unable to find a study that specifically examined whether there was (or was not) a link between irrigated areas and liquefaction in the Wenchuan earthquake, thus we highlight the importance of this topic for future research.

Irrigation has an important role in food security, yet in certain slope conditions it can contribute to amplified liquefaction hazard. Therefore, this potential increase in hazard should be considered in land-use practices, albeit with careful consideration of local context. A study that analysed liquefaction hazard due to wet rice cultivation recommends building mixed-crop cultivation into agricultural systems as a way to mitigate liquefaction hazard¹³. Mixed-crop cultivation can introduce dry areas that reduce the lateral connectivity of saturated areas and allows for deeper-rooting crops that help to stabilise the soil¹³. As a demonstration of this potential, breaks in the connectivity of saturated sediments as a result of groundwater extraction likely prevented lateral spreading during the 1999 Chi-Chi earthquake, Taiwan⁶⁵. Similarly, saturated, anaerobic conditions can be successfully replaced by drip irrigation or other techniques⁶⁶⁻⁶⁸ to reduce water use and greenhouse gas emissions, but such practices could have the co-benefit of reducing the liquefaction hazard in some situations. As one example, adaptive rice cultivation that trialled intermittent instead of continuous flooding was piloted with Balinese farmers, and resulted in increased rice yields and the potential for bottom-up, farmer-led change⁶⁹. Further research into such land-use practices that could help mitigate both excessive water consumption and liquefaction hazards, while also including local context and knowledge, should be a priority for sustainable development.

[H1] Compounding tsunami hazards

While the initial dimensions of an earthquake-generated tsunami are determined by the extent and height of the fault rupture itself, the coastal environment also effects the intensity of a tsunami as it reaches the coast and moves inland. Thus, anthropogenic coastal modifications can modify tsunami hazard. Such modifications can be both local (degradation or removal of vegetation and coral reefs, destruction of abiotic barriers such as sand dunes, and subsidence resulting from groundwater withdrawal or drainage of peatlands), and global (sea-level rise resulting from climate change) (Figure 3). We again highlight that we are choosing not to cover broader topics related to exposure in this Review, such as the construction of homes in tsunami-exposed areas or the construction of man-made tsunami defences^{70,71}.

[H2] Degradation of coastal ecosystems

Coastal ecosystems include mangrove and other coastal forests, seagrass beds, and coral reefs. These systems are usually linked to each other and to geological features; for example, mangroves and seagrasses bind soft sediments, allowing the development of coral reefs in areas that might otherwise have had too much silt for coral growth. Similarly, corals can shelter marine species and protect shorelines from wind-driven waves and erosion, thus encouraging the growth of coastal vegetation⁷².

In many areas, coastal ecosystems have been degraded or destroyed by human activity. For example, mangroves have been cleared for urban and industrial development, forestry, aquaculture, and agriculture^{15,73}. An estimated 35% of mangrove forest was lost globally between the 1980s and 1990s⁷⁴. Rates of mangrove loss vary widely. Some areas of Indonesia (which has been home to more than 20% of the world's mangrove areas) have seen losses of up to 75% compared to estimates from around 1800⁷⁵. Similarly, coral ecosystems are being impacted by human activities such as overfishing, pollution, habitat destruction, ocean acidification and ocean warming. Estimates state that there was an ~50% decline in coral cover globally over the period 1957—2007⁷⁶.

There is extensive scientific evidence for the important role that coastal ecosystems have in offering some protection of low-lying coastal areas from wind-driven and extreme-weather waves and storms⁷⁷. However, there remains considerable debate in the literature on the extent to which these ecosystems can reduce the magnitude of tsunami waves, which have higher velocity, are larger, and can be more energetic than storm waves⁷⁸. One reason for this debate is that the level to which coastal ecosystems might reduce hazard is very much dependent on the size and nature of the tsunami⁷². Coastal ecosystems can reduce the magnitude of a smaller tsunami (up to a few metres in height), but large tsunamis exceeding a few metres would likely surpass their capacity for any form of resistance. The height, period, number of waves, incidence angle of tsunami waves and local bathymetry and topography will all influence the level of resistance provided by coastal ecosystems⁷⁹.

The type and health of a coastal ecosystem will also influence its protective role. Key factors include species composition, maturity, tree size and flexibility, vegetation density and health^{80,81}. For coastal forests, having a range of different tree crown heights is likely important⁷². By this measure, primary growth coastal forests, that is a forest that has remained relatively undisturbed by human activity, will likely be more effective than a new plantation with only one species. Where plantations are utilised in coastal settings the type of tree is also likely a factor, in one example of the impact of species type

Casuarina trees were shown to provide greater resistance than palm trees for the 1998 Papua New Guinea tsunami⁸². Offshore, seagrass beds can effectively serve as an extension of the land and thus diffuse wave energy, but again their effectiveness depends on the breadth and density of the seagrass meadow, as well as the water depth⁷². Similarly, the influence of coral reefs on tsunami waves is complex and a function of coral morphology. Unfragmented and healthy reefs that are at least a few hundred meters from the shore will provide the greatest opportunity for some reduction in tsunami energy^{72,83}.

Gaps and areas of degradation in coastal vegetation or coral reefs can not only decrease their protective capability but can result in worsened tsunami impacts for some areas as water is funnelled through the gap with a resulting concentration of tsunami energy⁷². Unhealthy corals or vegetation are also likely to be more vulnerable to destruction and thus to becoming a source of debris that amplifies the inland impacts of a tsunami.

The majority of scientific studies on coastal ecosystems and tsunamis were based on the 2004 Indian Ocean earthquake and tsunami. This tsunami was particularly large, with run-up heights exceeding 30 m in nearby Aceh, Indonesia⁸⁴. It is therefore unlikely to be representative of the potential hazard reduction presented by coastal ecosystems against small to moderate tsunami less than a few metres high. While there are many site-specific or anecdotal reports on the protective nature of native coastal ecosystems for the 2004 event^{85,86}, some of the more spatially broad and rigorous studies reported only limited hazard reduction resulting from coastal vegetation⁸⁷. However, a study based on multiple information sources such as satellite imagery and local ecological parameters estimated that, while distance to coast was the dominant determinant of impact, coastal vegetation reduced casualties by ~5%, which is a clear benefit to public safety⁸⁸ (Figure 3).

Coastal ecosystems will not reduce tsunami hazard under all circumstances, but answering the question of which types of vegetation might have a role, and under which circumstances, remains an important area for future research. Coastal ecosystems can reduce tsunami hazard in certain circumstances but should never be considered a complete solution; buffer zones, early-warning systems, tsunami evacuation towers, sea walls, and land-use planning are also essential mitigation measures. However, communities should be encouraged to maintain and restore coastal green belts as part of a larger tsunami risk reduction strategy. These nature-based solutions should be considered a valuable and economical means to providing tsunami hazard reduction, along with a host of other benefits to ecosystem services and climate change mitigation⁸⁹. Hybrid approaches combining natural elements and engineered protections, such as tsunami mitigation parks (intentionally designed hillsclapes with vegetation), can also be an important hazard mitigation option⁹⁰.

[H2] Destruction of abiotic barriers

Many coastlines are buffered from waves by abiotic systems that include beaches, sand dunes, and mudflats (Figure 3). These systems can reduce tsunami wave energy through wave shoaling and breaking, and in some cases can act as a barrier^{72,91}. Abiotic coastal systems are geomorphically dynamic, and can be impacted by humans through construction, development, removal of sediment, erosion resulting from removal of vegetation, and sea-level rise.

In the case of the 2004 Indian Ocean tsunami, a notable example was made of a hotel in Yala, Sri Lanka. The hotel was completely destroyed by the tsunami, because during its development the

seaward sand dunes were removed in order to improve the view from the hotel⁹². The complete destruction of the hotel during the tsunami stands in stark contrast to neighbouring areas that experienced less damage due to their locations behind unaltered sand dunes. This example also illustrates that gaps in protective systems can result in channelling of water and increased wave energy at unprotected locations.

[H2] Relative sea-level rise

Relative sea-level change is defined as a change in the distance between the sea surface and the land height. Relative sea-level rise can thus be the result of increases in the sea-surface height (from ocean warming and thermal expansion, melting of glaciers, and other ocean processes)¹⁷ or a local drop in land height (subsidence due to underground resource extraction, loading from the weight of buildings, glacial isostatic adjustment, or tectonics)⁹³⁻⁹⁵.

Relative sea-level rise can make a coastal area more vulnerable to tsunami destruction as a consequence of greater inundation distance and wave height over land as well as reduced rate of drainage after the tsunami, thus a longer period of inundation. The 1964 Niigata earthquake and tsunami provides an illustration, as urbanisation and industrialisation in Niigata City, Japan and the ensuing rapid extraction of groundwater, had led to rapid land subsidence of rates as much as 56 cm yr⁻¹, and a total of 1 to 3 m of land subsidence in the period ~1955 to 1963⁹⁶. This subsidence amplified the effects of the 1964 tsunami, where substantial areas of the city were affected⁹⁶ and water remained in flooded areas for a considerable time⁹⁷. Climate-related sea-level rise will likely have similar consequences.

[H1] Coastal flooding

While tsunamis represent a sudden and temporary inundation of the coast due to the motion of seawater in a large wave, coastlines can also be flooded for years to decades due to changes in land height resulting from tectonic deformation of the Earth's crust. Tectonic deformation can result in up to several metres of land-height change (that is, relative sea-level change), with both uplift and subsidence potentially detrimental to communities living in affected areas, thus posing an additional earthquake hazard to coastlines.

[H2] Tectonic and anthropogenic relative sea-level change

As an example of the magnitude of potential tectonic land-height change, ~420 km of the Japanese coastline experienced >1 m of coseismic subsidence during the 2011 M_w 9.0 Tohoku-oki earthquake⁹⁸. Postseismic deformation can also have dramatic impacts on relative sea level, with mantle relaxation from great earthquakes causing (over many decades) land-height change over a wide region. For example, areas of Thailand witnessed postseismic subsidence at rates of up to 1 cm yr⁻¹ as the Earth's mantle relaxed after the 2004 Indian Ocean earthquake⁹⁹. In 2010-2011 a combination of tectonic deformation and anthropogenically enhanced liquefaction resulted in subsidence of >0.5 m in some areas of Christchurch¹⁰⁰, meaning that these regions experienced the equivalent of several centuries of current rates of climate-related sea-level rise.

Sea-level rise from human activities – both in terms of global climate change and localised subsidence from extraction of resources -- will compound flooding from tectonic land-height change. It will be

important for researchers to assess potential land area that could be inundated as a result of the compound effects of climate-related sea-level rise, anthropogenic subsidence, and tectonic land height change. The compound effects should be included in plans for mitigation of coastal flooding. To support this, efforts should be made to make modelling of land-height changes from plausible scenario earthquakes available to local decision-makers. Given that earthquake-related changes can be instantaneous, it is important to prepare for them with the backdrop of other processes for sea-level rise.

[H1] Summary and future directions

In this Review, we highlight that ongoing environmental and landscape degradation by human activities leaves these systems more vulnerable to destabilization during earthquakes (Figure 4). Human activities such as modification of slopes, construction of roads in mountainous areas, and modification of vegetation and hydrological systems can increase the probability and extent of earthquake-triggered landslides. Reclamation of land and raising of the water table through irrigation or relative sea-level rise can increase liquefaction hazards. Removal or degradation of coastal ecosystems and adiabatic systems can, for smaller tsunami of less than a few meters height, amplify tsunami hazard, which can also be elevated by relative sea-level rise. Anthropogenic sea-level rise and coastal subsidence can also increase coastal flooding resulting from tectonic deformation of the Earth's crust. These amplified hazards occur in addition to social considerations of exposure and vulnerability. Environmental modification has increased the overall impact 'footprints' of modern earthquakes compared to their prehistoric counterparts; for example, rockslides for prehistoric earthquakes in New Zealand travelled less far than those for those for earthquakes that occurred after anthropogenic deforestation³⁸. We recommend that future research should prioritize exploring the co-benefits of sustainable practices in restoring and stabilizing landscapes so they are less susceptible to failure during earthquakes.

Unsustainable farming and/or deforestation practices, primarily driven by immediate economic objectives, can reduce the stability of hillslopes and increase the risks of landslide and liquefaction hazards. The 2018 Palu case (Box 2) highlighted how irrigation can amplify liquefaction hazards, with saturated soils on low-angle slopes experiencing substantial flowslides during the earthquake^{13,14}. Further quantitative analysis of the influence of irrigation on liquefaction and landslide hazards in other locations over the historical earthquake record could address questions of where irrigation amplified these hazards in the past, and which areas could be susceptible to such events in the future. Sustainable rice-paddy irrigation practices, for example, drip irrigation or other techniques that reduce water use by successfully replacing saturated soil conditions, could have the co-benefit of reducing the liquefaction hazard in addition to reducing greenhouse gas emissions.

Nature-based solutions, primarily designed for their carbon emission or pollution remediation potentials, can also help restore landscapes and aid mitigation of secondary earthquake hazards. For example, restoring natural coastal ecosystems and habitats with sand dunes, beaches, mangrove forests and seagrass meadows, can provide some protection against tsunami, but there are limitations to their mitigation potential for tsunamis over a few metres high. Even though coastal ecosystems do not provide full protection against tsunami, their potential for limited hazard reduction along with a host of other ecosystem services and climatic benefits should be an argument for preserving and restoring them as much as possible. However, coastal bioshields should be managed sensitively and in collaboration with local communities, as they can be misused if non-native mono-culture plantations are used to replace primary vegetation, which disrupts local ecosystems. For example, there are a

number of examples of primary growth vegetation being replaced with exotic *Casuarina* plantations with the reasoning the plantations are more protective, or sand dunes being flattened to make way for such plantations¹⁰¹. In southeast India the bioshields concept gained traction following the 2004 Indian Ocean Tsunami, resulting in vast plantations of exotic trees (mainly *Casuarina* species) to act as bioshields. These plantations occurred despite various local issues including violations of indigenous land rights, removal of sand dunes, and loss of biodiversity¹⁰¹.

In many countries, the history of the landscape is intimately connected with the impacts of colonial history and its ongoing repercussions, as briefly highlighted in the example case studies (Boxes 1-2). It is important that future research continues to critically examine how colonial history can contribute to modern-day disasters. Research should examine these factors in other locations and extend the analysis to include economic and social vulnerability.

Traditional and indigenous knowledge often promotes protection of ecological diversity and environmental stewardship^{102–104}, which are important features of a resilient system¹⁰⁵, so could thus offer a rich source of potential solutions to mitigating secondary earthquake hazards with combined social and ecological co-benefits¹⁰⁶. For example, in Haiti, sustainably managed woodlots (traditionally called “rak bwa”) by local farmers is contributing to regeneration of forest cover¹⁰⁷, and could thus be a partial solution towards reducing landslide hazard. In West Sumatra, Indonesia, preservation of forests and mangroves are rooted in local culture, and traditional building techniques are environmentally friendly as well as earthquake resistant¹⁰⁸. While traditional knowledge has been identified as an important source of solutions for mitigating earthquake risk, including more earthquake-resistant construction, evacuation for tsunamis, and community organising for disaster preparedness and response¹⁰⁹, we found little research has been done on its relation to secondary earthquake hazards, and highlight this relationship as a priority for future research. Understanding the significance of anthropogenic actions in causing the climate crisis underscores the importance of scrutinizing the environmental footprint of humans. However, the necessity for vigilance extends beyond climate alone; the emerging research into the ramifications of human activities on secondary earthquake hazards, as highlighted in this Review, further emphasizes the critical need for heightened caution around the impacts of human activities. The evidence reviewed here highlights a pressing requirement for society to diligently consider and mitigate its impacts on the Earth, acknowledging the broader spectrum of potential geological consequences.

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Competing interests

The authors declare no competing interests.

Author contributions

E.H. conceptualised the review, coordinated the process, and wrote the preliminary draft with the help of J.M. All authors contributed to discussions, planning, writing, and review of the manuscript. S.S. developed the graphics.

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Tables

Table 1 | **Human environmental modifications influencing secondary earthquake hazards.**

| Secondary earthquake hazards | Human-caused changes to the environment | | | |
|-------------------------------------|-------------------------------------------------------------|------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|-----------------------------------------------------|
| | Movement of earth | Hydrological changes | Ecosystem changes | Climate change |
| Landslides | Road construction; loading or unloading of slopes | Changes in drainage patterns | Deforestation on slopes; changes in agricultural land cover; abandonment of cultivated land | More intense precipitation; more storms; more fires |
| Liquefaction | Land reclamation and deposition of loose sediments | Groundwater withdrawal; irrigation; modification and reclamation of river channels | Removal of vegetation | Sea-level rise; changes in precipitation |
| Tsunami | Removal of sand dunes and barriers | Groundwater withdrawal leads to subsidence; river dams cause changes to coastal sedimentation rates. | Removal of coastal vegetation; destruction of coral reefs | Sea-level rise; bleaching of corals |
| Flooding or land submergence | Land reclamation resulting in subsidence and sea-level rise | Groundwater withdrawal leads to subsidence | Destruction of peatlands resulting in subsidence | Sea-level rise |

Figures (NOT FINAL VERSION)

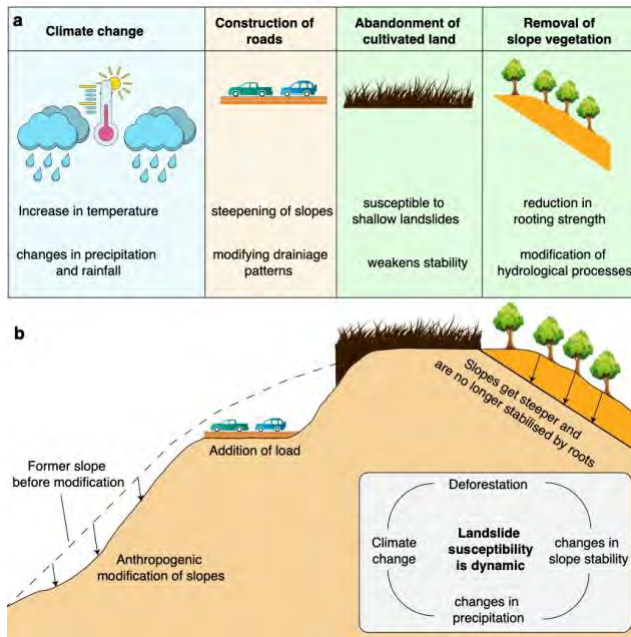


Figure 1. **Anthropogenic influences on landslide hazards.** Primary human-caused environmental modifications include the impacts of climate change (such as increased temperatures and changes in precipitation), construction of roads, abandonment of agricultural land, and removal of slope vegetation (such as deforestation). These factors decrease slope stability and make them more susceptible to landslide.

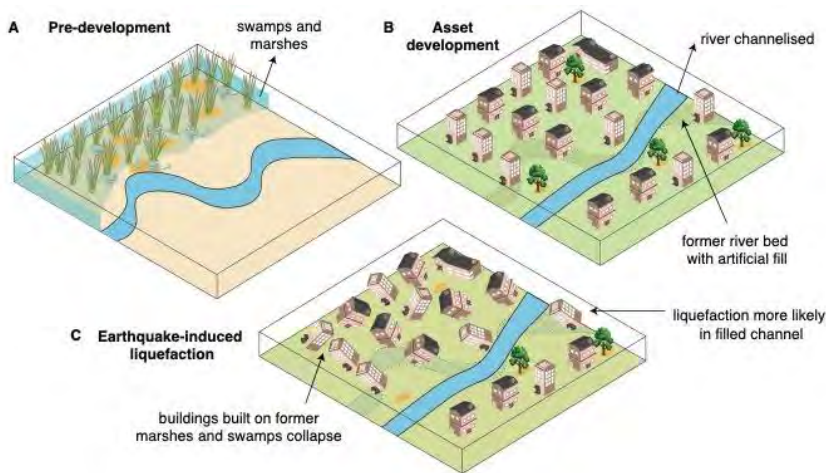


Figure 2. **Anthropogenic influences on liquefaction hazards.** a | Example of an original landscape, comprising of swamps, a meandering river and a region of exposed bedrock. b | the same landscape after land reclamation and asset development. The river is artificially channelised and the original river bed is filled with artificial till. The marshland is removed for development. c | After modification, the paleochannel and reclaimed swamp or marsh land represent elevated liquefaction hazard because these anthropogenic fill layers contain unconsolidated, saturated soils that experience increased pore-fluid pressure and loss of strength during an earthquake. The buildings on the bedrock

and outside of the reclaimed land are less likely to experience liquefaction. The concept of this figure was inspired by case studies from Christchurch, New Zealand^{48–50,52,53}, but is applicable to many other regions.

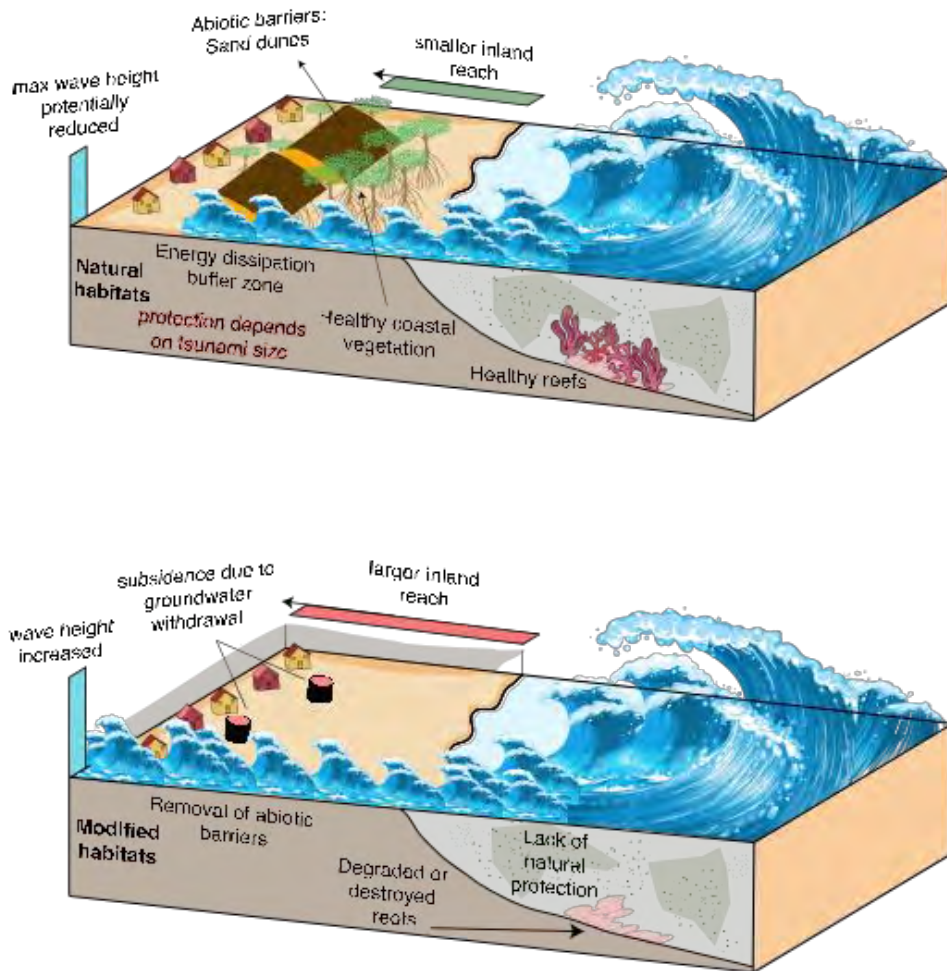


Figure 3. **Anthropogenic influences on tsunami hazard.** a | Illustration of the potential benefits of natural coastal habitats consisting of healthy coral reefs and marine life, coastal forests, and sand dunes in mitigating tsunami hazards. These natural ecosystems can act as a buffer zone by decreasing the maximum wave height and inland reach of a tsunami. However, the effectiveness of these defences depends on tsunami size. b | Anthropogenically modified coasts can have one or more of the following: relative sea-level rise from subsidence related to excessive groundwater withdrawal, and degraded or destroyed natural ecosystems, such as coral reefs, mangroves, seagrass meadows, removal of sand dunes. These anthropogenic modifications can lead to local amplification of tsunami hazards, such as increased inland reach.

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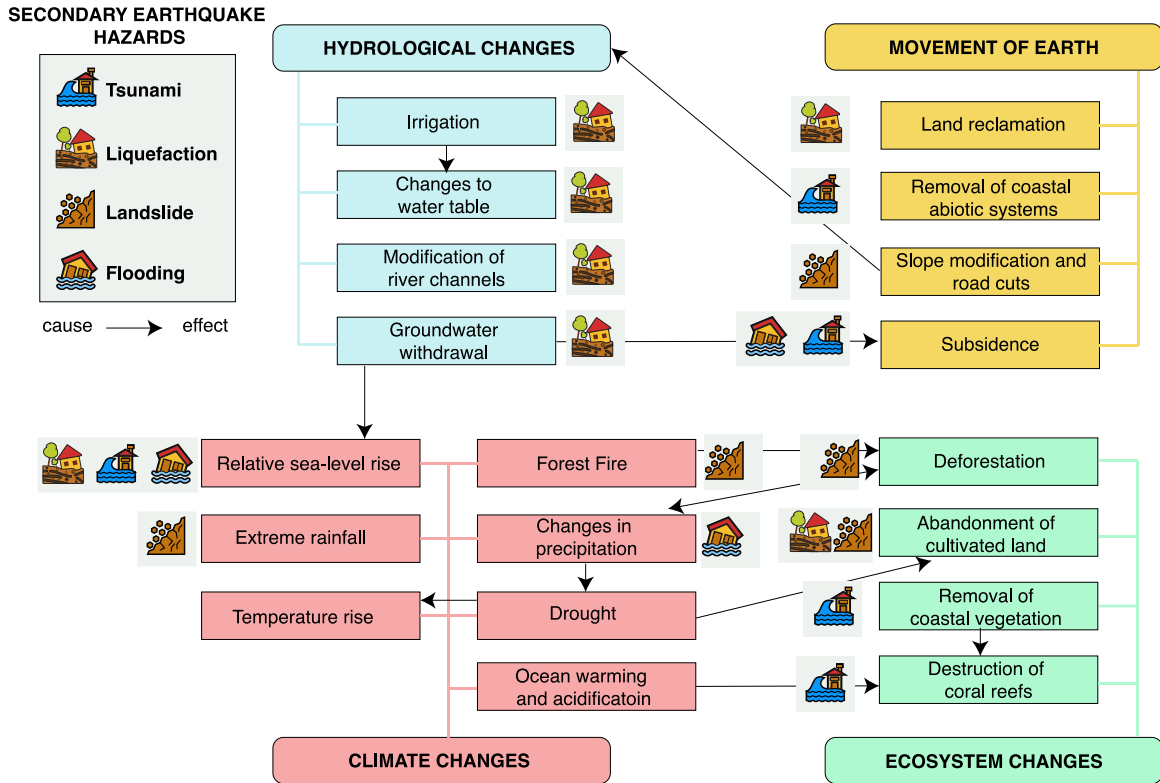


Figure 4. Interactions between various human environmental modifications and earthquake secondary hazards. Human activities and their impacts are denoted in boxes, while the corresponding secondary earthquake hazard is depicted by the hazard symbol. For example, groundwater withdrawal (human activity) can lead to increased liquefaction risk (secondary earthquake hazard) and can also contribute to relative sea-level rise. Relative sea-level rise in turn increases the risk of post-earthquake flooding, tsunami and liquefaction. The arrows represent the most direct, substantial influences among human activities, and not all the feedbacks can be shown here. For example, relative sea-level rise can reduce the space available for mangroves (where they abut developed areas), which could further increase tsunami hazard.

Boxes

Box 1 | The 2010 and 2021 Haiti Earthquakes

The 2010 M_w 7.0 and 2021 M_w 7.2 Haiti earthquakes provide examples of how a combination of environmental and economic pressures can result in environmental degradation and increased secondary earthquake hazards. They also illustrate the necessity of understanding a region's entire social and environmental history to comprehend such disasters more fully, hence we touch on aspects of social vulnerability and exposure in this Box (otherwise outside the scope of this paper) in order to provide a more holistic overview of these disasters. These two events resulted in 220,000-316,000¹¹⁰ (official estimates vary broadly) and >2,200 casualties, respectively, and the region has not yet recovered from these disasters. The devastation in Haiti was triggered by a combination of primary and secondary hazards affecting a densely inhabited area and highly vulnerable communities. Homes built with brittle and heavy materials -- often providing good resistance to hurricane winds -- could not withstand strong earthquake shaking, and a lack of substantial earthquakes in community memory meant that the region was ill-prepared for such an event^{110,111}.

Both the 2010 and 2021 earthquakes also triggered secondary hazards across the region. During the 2010 event, the location of the city of Port-au-Prince, built on an alluvial coastal plain, led to liquefaction around the port, coastal areas and adjacent to rivers⁵³. In both the 2010 and 2021 events, thousands of landslides¹¹² were triggered on largely deforested slopes (see the Box figure), including in dense urban areas. Buildings on unstable slopes were particularly vulnerable during the 2010 earthquake in Haiti. Despite visible signs of land movement and localised landslides triggered by the earthquake, these same slopes were sites for temporary camps (see the Box figure), building new vulnerability. In addition, the 2010 event triggered local tsunamis of up to 2 m height, caused by both seafloor uplift and submarine landslides¹¹³.

Many have argued that social and physical vulnerability set the stage for such widespread devastation, and this vulnerability can be traced back to Haiti's colonial history, external exploitation, and the numerous subsequent neo-colonial foreign interventions¹¹⁴⁻¹¹⁶. Such historical events include colonisation and slavery, a hard-won battle for independence, an unjustified and burdensome reparation debt, successive eras of military rule, dictatorships, and external interventions. These events have created enduring social and environmental challenges, setting the background for persistent patterns of disaster vulnerability¹¹⁷.

Part of this history is widespread environmental degradation, that likely amplified secondary hazards during the 2010 and 2021 earthquakes. Deforestation began in force in the late 1600s as the French colonizers organised clearing of forests for plantations. Following Haiti's successful slave rebellion and independence in 1804, the French government demanded an unjustified compensation through a "reparation debt" under threat of military action, aimed at compensating plantation owners for lost revenue from slavery. Part of this burdensome financial obligation paid by Haiti through the sale of mahogany, which further exacerbated the strain on the country's forested areas¹⁰⁷. The current level of forest cover is debated, but scientific remote-sensing estimates suggest that forest cover is >30%¹¹⁸ (much higher than the commonly quoted statistic of 2% of original forest cover), but likely reflects regrowth at farmer-managed woodlots¹⁰⁷. The extensive history of deforestation has been linked to weakening slopes and landslides. In addition, deforestation leads to shortages of quality wood needed for construction, including traditional timber buildings, which are more resistant to earthquakes and hurricanes¹¹⁹.



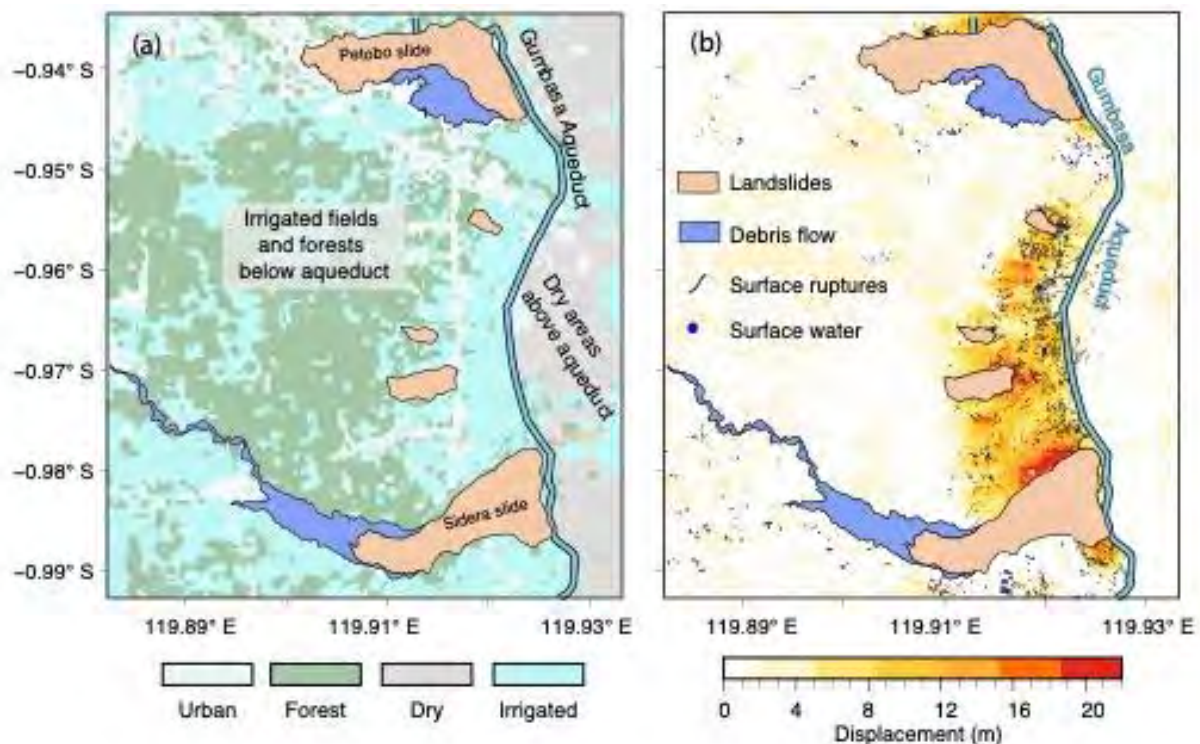
Box 2 | **The 2018 Palu (Indonesia) Earthquake**

The 2018 Mw 7.5 Palu earthquake of Sulawesi, Indonesia, claimed >4000 lives and displaced >200,000 people¹²⁰. The event demonstrates the damage that can occur as a result of cascading events combined with extensive anthropogenic modification of the environment. The damage from environmental modification compounded basic issues of exposure and vulnerability, including those from communities who were living in a tsunami inundation zone known from historical tsunamis^{121,122} and that many houses were not built to withstand heavy shaking¹²³. Hence, we touch on aspects of social vulnerability and exposure in this Box (otherwise outside the scope of this paper) in order to provide a more holistic overview of this event.

A tsunami generated by the 2018 Palu earthquake reached over 300 m inland, with localised inundation heights of >8 m^{124,125}. Coastal ecosystems such as coral reefs and mangroves had been extensively cleared over the last century¹²⁶. The tsunami waves had relatively short wavelengths and periods, which likely indicated subsea landslides were a major contributor to the tsunami¹²⁷, suggesting coastal ecosystems could have been able to provide some level of protection by increasing surface roughness at the coast and reducing the velocity of the tsunami wave, and in turn reducing the inundation distance. In addition to the impacts of the tsunami, coastal flooding was observed on the eastern side of Palu Bay. Eyewitnesses described a sudden increase of sea level that flooded their houses, likely the result of coseismic subsidence¹²⁵. On the steep eastern and western coasts of Palu Bay, poorly built land reclamations that supported local gravel mining operations completely slumped into the sea generating additional tsunamis¹²⁷.

Large-scale irrigation works were constructed at the beginning of the 20th century by the Dutch colonial government of the East Indies, who occupied Sulawesi from 1905 to 1942, to ensure reliable rice cultivation¹²⁸. The Gumbasa aqueduct was used to raise the water table to near-surface levels to provide a consistent water supply to rice paddy fields down-slope (see the figure, part a), but with the

consequence of saturating sandy alluvial soils. The irrigated area below the aqueduct experienced extensive liquefaction, lateral spreading and flowslides after the 2018 earthquake (see the figure, part b), which were responsible for a substantial majority of the casualties^{13,14,120}. The saturated soils liquefied during the earthquake, resulting in extensive lateral spreading (flowslides) on slopes as gentle as 1° ^{13,14,120}. Both remote-sensing data and field surveys confirmed the correlation of large-scale flowslides to irrigated areas with little forest. The flowslide displacements were >15 m in some areas (measured using sub-pixel correlation of pre- and post-event Planet Labs satellite imagery, figure part b) and were clearly linked with wet rice cultivation in the valley (see the figure). These flowslides also modified the post-earthquake hydrology, resulting in flash flooding in the months following the earthquake¹²⁹. Additional hazards associated with the aqueduct included debris floods, where water mixed with debris contributed to the flowslide and liquefaction damage¹²⁰. It is notable that an earthquake in 1927, near the time of the aqueduct's construction, caused extensive damage in Palu but with no reports of liquefaction or flowslides^{130,131}, indicating the soils were not saturated before the aqueduct's construction.



The Box figure is inspired by [NASA](#) and replotted with data from Ref. ¹³.