Earth's Future

Key Points:
- The number of countries suffering from consecutive disasters is increasing, and their impacts can be distinctly different from single disasters
- An overview is provided of the state-of-the-art in the understanding of consecutive disasters as discussed in the literature
- As current scientific models and policy settings do not allow to properly assess the risk of consecutive disasters and their impacts, we identify a roadmap for the future

Supporting Information:
- Supporting Information S1

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Why We Can No Longer Ignore Consecutive Disasters

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Abstract In recent decades, a striking number of countries have suffered from consecutive disasters: events whose impacts overlap both spatially and temporally, while recovery is still under way. The risk of consecutive disasters will increase due to growing exposure, the interconnectedness of human society, and the increased frequency and intensity of nontectonic hazard. This paper provides an overview of the different types of consecutive disasters, their causes, and impacts. The impacts can be distinctly different from disasters occurring in isolation (both spatially and temporally) from other disasters, noting that full isolation never occurs. We use existing empirical disaster databases to show the global probabilistic occurrence for selected hazard types. Current state-of-the art risk assessment models and their outputs do not allow for a thorough representation and analysis of consecutive disasters. This is mainly due to the many challenges that are introduced by addressing and combining hazards of different nature, and accounting for their interactions and dynamics. Disaster risk management needs to be more holistic and codesigned between researchers, policy makers, first responders, and companies.

1. Introduction

Consecutive occurrences of natural hazards are prevalent in many parts of world. A recent example is Japan's summer of 2018: The country was hit on 18 June by the Osaka earthquake (moment magnitude scale $M_w = 5.5$) killing four people (USGS, 2018a). This was followed by flooding between 28 June and 8 July caused by torrential rain, which was Japan's deadliest flood since 1983. With $10 billion in damages, this became the second costliest weather event of 2018 (Kornhuber et al., 2019; LeComte, 2019 ; Tsuguti et al., 2019). Subsequently, the flooding caused landslides, which together killed 246 people (LeComte, 2019; Tsuguti et al., 2019). Next, from 14 until 25 July the country was hit by a heatwave, in August several typhoons and tropical storms hit Japan's main island (Typhoon Cimaron made landfall close to Kyoto), and on 4 September Typhoon Jebi struck Japan (Japan Meteorological Agency, 2018; LeComte, 2019; Li et al., 2019). Typhoon Jebi became the strongest typhoon to hit the country in 25 years, killing at least 14 people and injuring over 600 (FDMA, 2018; LeComte, 2019). Typhoon Jebi was followed only 1.5 days later by an earthquake in Hokkaido ($M_w = 6.7$), triggering mudslides, killing at least 41 people and leaving around 3 million people without power (BBC, 2018; USGS, 2018b). In another example, a succession of storms in southern England during the 2013/2014 winter caused severe floods and exacerbated insured losses to £451 million, which exceeded previous recent large flood events such as the 2005 Carlisle floods (£272 million) and the 2009 Cumbrian floods (£174 million) (Schaller et al., 2016). Haiti suffered from a $M_w = 7.0$ earthquake in 2010, while still recovering from several tropical cyclones that hit the island 18 months earlier. The earthquake became the deadliest in its history, leaving 1.5 million people homeless (Gorum et al., 2013) and subsequently contributing to the return of cholera after more than a century of absence, placing additional pressure on health and emergency response facilities (Date et al., 2011).

The above examples show the different spatial and temporal ranges at which consecutive disasters can occur, ranging from days to months and years apart, depending on the recovery rate. Disasters occur when a hazard coincides with exposure and vulnerability. All these three risk components are dynamic (UNDRR, 2016), with the potential to increase or decrease in response to the occurrence of a previous hazard or disaster (Peduzzi, 2019). We refer to Box for our definition of consecutive disasters. Understanding consecutive disasters is part of a multihazard approach, defined by the United Nations Office for Disaster Risk Reduction (UNDRR;, 2016) to mean "(1) the selection of multiple major hazards that the country faces, and (2) the

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specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects" (UNDRR, 2016, p. 19). Gill and Malamud (2014) discuss four key factors to be taken into account when developing multihazard approaches: (1) a comparison between different individual hazards for a predefined area, (2) all possible interactions between hazards, (3) the impacts of spatially and/or temporally coinciding hazards, and (4) dynamic vulnerability.

Box 1 : Consecutive Disasters Defined

Throughout this paper, we use the term "consecutive disasters" to mean two or more disasters that occur in succession, and whose direct *impacts* overlap spatially before recovery from a previous event is considered to be completed. This can include a broad range of multihazard types, such as compound events (Zscheischler et al., 2018) and cascading events (Pescaroli & Alexander, 2015). It is important to mention that the latter also includes Natech events where a natural hazard contributes to a disaster that then impacts industrial facilities and infrastructure (Girgin et al., 2019; Krausmann et al., 2017) *(see Box 2)*. Natech disasters, and the contributions of anthropogenic processes, such as land use land cover changes, which trigger or exacerbate natural hazards (Peduzzi, 2019), are often excluded from multirisk assessment (Girgin et al., 2019).

It is also important to recognize the role of the *impacted entity* in defining the spatial scale of the direct impacts and in defining when recovery is completed. For example, at a local community scale, two tropical cyclones are less likely to directly hit the same village during cyclone season. For example, the Philippines is hit by approximately 20 cyclones each year (UNOCHA, 2017). Hence, at a national scale these sequential disasters would be considered consecutive disasters, while individual villages are likely to only suffer damages from one of those cyclones in a season, which for them would not be considered consecutive. Conversely, the duration of recovery after a first event can be longer at a local scale if tourists now decide to visit another part of the country, while at a national scale the flourishing of tourism in a different part of the country balances the economic impacts.

In the context of our study, direct impacts are interpreted in a broad sense encompassing both tangible and intangible direct impacts, with examples including damage to physical infrastructure, loss of lives, decreasing the capacity of key institutions (e.g., hospitals), and welfare. Consecutive disasters can occur due to dependency between natural hazards (e.g., triggering events) or when independent hazards occur in the same space-time window. Figure 2 is a schematic representation of dependent and independent consecutive disasters, showing different degrees of recovery using the quality of the built environment as an impact variable. We refer to different disasters as the first, second, third, etc. disaster based on their occurrence overtime, not on the scale of their impact.

The development of such multihazard approaches are strongly advocated for in the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015) and its predecessor the Hyogo Framework for Action (UNDRR, 2005) and were also high on the agenda in the last UNDRR's Global Platform 2019 (UNDRR, 2019). The Paris Agreement also calls for the development of *comprehensive risk assessments* (United Nations, 2015). Moreover, within the social sciences and governance research communities, there have also been calls for the generation of multirisk knowledge (Cutter, 2018; Scolobig et al., 2017). For example, Scolobig et al. (2017) proposed a multirisk governance framework, stating there is an urgent need to improve the scientific foundations of multirisk assessments. Our manuscript addresses this research gap that is called for in the governance literature by improving the fundamental understanding of multirisk assessments.

The recent disasters described above support the notion that the challenges a community faces when being hit by a subsequent disaster while still recovering from an earlier disaster are substantially different than the impacts of two static events (Tarvainen et al., 2006). Nonetheless, universal disaster risk reduction (DRR) and disaster risk management (DRM) frameworks to address consecutive disasters from a modeling (AghaKouchak et al., 2018) and an institutional perspective (Scolobig et al., 2017) are still missing. In this article, we first discuss the occurrence and impacts of consecutive disasters around the world (section 2), before proceeding to use existing literature to explore the specific challenges faced when assessing consecutive disasters (section 3). We respond to this set of challenges with a roadmap to advance understanding of consecutive risk at a global, regional, and local scale (section 4).

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2. Consecutive Disasters Explained

The occurrence of each disaster in a sequence (Gill & Malamud, 2016) and the amount of time in between two disasters (Marzocchi et al., 2012) can substantially change the vulnerability to the next hazard. For example, Gill and Malamud (2016) demonstrate this for consecutive disasters in Nepal and Guatemala. Others have characterized the spatial overlap of multiple natural hazards (either independent or dependent) in a given region (e.g., Carpignano et al., 2009; Eshrati et al., 2015; Forzieri et al., 2016; Tate et al., 2010), which demonstrates the possibility of consecutive disasters occurring.

The widespread distribution of natural hazards, with some hazard types affecting large spatial regions of 10^4 to 10^8 km^2 (Gill & Malamud, 2014), demonstrates that this problem is not geographically isolated but relevant to many, if not all, parts of the world. Recently, there has been discussion about the use of the word *natural* when referring to natural disasters (Bacigalupe, 2019). Disasters occur when a hazard interacts with exposure and vulnerability of people and other elements. It is also important to note that people influence climate change, and hence, climate change-induced hazards could be perceived of as unnatural (Peduzzi, 2019). For simplicity reasons, in this paper we will refer to both climate change-induced and geophysical hazards as natural hazards but refrain from using the term "natural disasters." In this section, we discuss the science behind consecutive disasters, first outlining the different typologies, then the causes, occurrences, and finally the impacts.

2.1. A Typology of Consecutive Disasters

Figure 1 shows examples of different types of consecutive disasters, their causes, where they occurred, and their impacts. Generally, the literature recognizes the following four types of consecutive disasters (Gill & Malamud, 2014): (1) independent hazards having a spatiotemporal coincidence (Tarvainen et al., 2006), (2) a first hazard that triggers other hazard(s) (Tarvainen et al., 2006), and (3) the occurrence of one hazard that alters environmental circumstances and thereby *increases* or (4) *decreases* the probability, frequency, or magnitude of another hazard (Kappes et al., 2010). Another interaction distinction made in the literature is that of unidirectional versus bidirectional, where the former is defined as a primary hazard followed by a secondary hazard, and the latter includes feedback mechanisms from the secondary hazard influencing the primary hazard (Gill & Malamud, 2016). For example, a flood may trigger a landslide, which exacerbates the flooding. These hazards can include both natural and anthropogenic hazards (Gill & Malamud, 2014), while acknowledging that there is no clear distinction between the two.

Independent hazards (as shown on the left-hand side of the bottom panel in Figure 2) are those hazards whose impacts spatially and/or temporally overlap while the hazards themselves are neither triggered by one another nor do they influence one another's probability of occurrence. An example of this is a tropical cyclone followed by an earthquake, as in the example of Haiti in section 1. Consecutive disasters can be the result of repeated occurrences of one hazard type (such as the sequence of flood events in the United Kingdom), or occurrences of multiple hazard types (such as the tropical cyclones and earthquake events in Japan and Haiti).

Dependent hazards (on the right-hand side of Figure 2) include triggering and cascading disasters, such as landslides triggered by a flood, or fires caused in the aftermath of an earthquake (Daniell et al., 2017). Cascading events are commonly defined as a primary hazard triggering a secondary hazard (Pescaroli & Alexander, 2015). For example, landslide activity may be greater in the months following an earthquake event due to changes in slope conditions (Daniell et al., 2017). An important subcategory of cascading hazards to mention are those where natural hazards trigger technological failures/hazards (so called
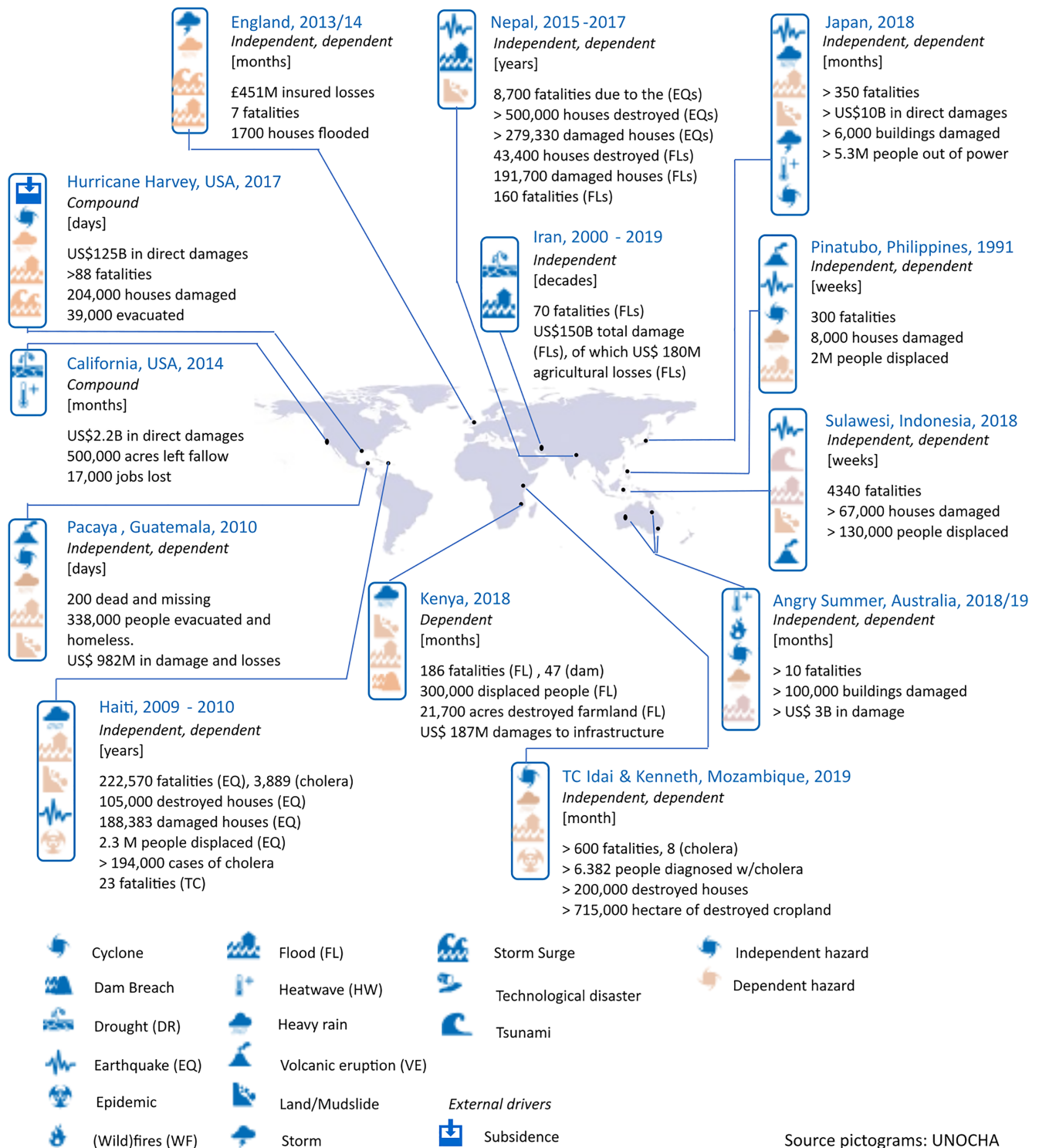
Figure 1. Examples of recent consecutive disasters. Examples of different types of consecutive disasters, showing disasters that occurred successively while recovery of the earlier disaster was still under way and impacted the same geographical area, its hazards and/or drivers, the time scale at which they occurred between brackets [], (estimates of) direct and indirect damages (in US$), and the number of people affected (sources: AghaKouchak et al., 2014; CFE-DMHA, 2010; Date et al., 2011; Gorum et al., 2013; LeComte, 2019; ReliefWeb, 2019; Schaller et al., 2016).
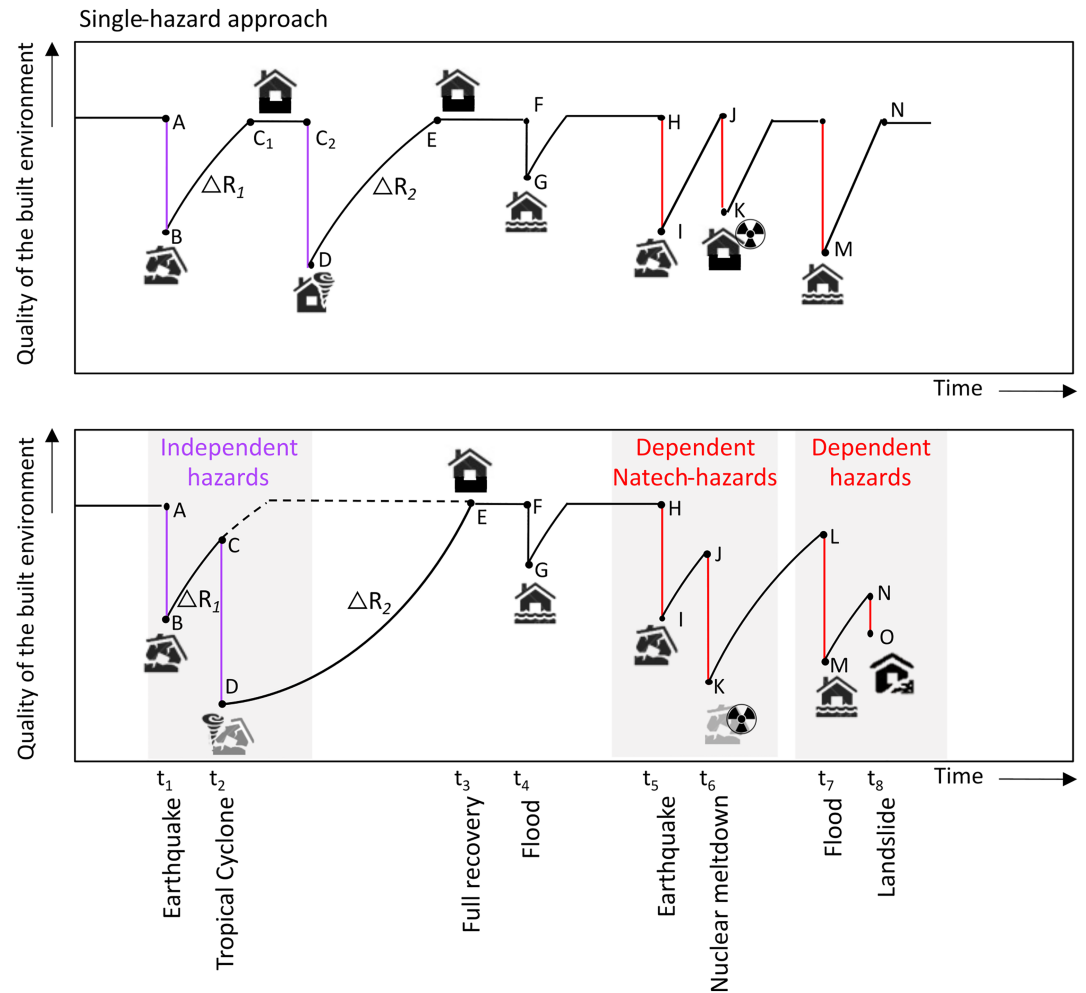
Figure 2. Different dimensions of impact: temporal dynamics. Schematic representation showing two features: (1) the difference between single risk (top panel) and consecutive risk assessments (bottom panel) and (2) differences between dependent and independent consecutive disasters and their different degrees of recovery at a given spatial scale (bottom panel). This is couched upon the work by (Zobel & Khansa, 2014). (1) The y axis can denote any indicator of impacts. Here we use the quality of the built environment as it is impacted by disasters, but this can be changed based on the stakeholder. The top panel shows how often the postdisaster risk level is considered to be identical to the predisaster level and independent of the amount of time in between events and the number of earlier disasters. (2) The difference in slope between R_1 and R_2 in the bottom panel denotes different recovery speeds, which indicates resilience. The earthquake and a tropical cyclone event at respectively t_1 and t_2 are independent hazards but are considered consecutive due to the short time window in between the two events and therefore their impacts are considered to be dependent— unlike the common single-hazard approach in the top panel. The event at t_4 is a single hazard, nonconsecutive disaster, while the events at t_5 and t_6, and t_7 and t_8 are consecutive disasters caused by dependent hazards where in the case of t_5 and t_6 the earthquake triggered a nuclear meltdown and in the case of t_7 and t_8 a flood resulted in a landslide. The impact of the events (at t_6 and t_8) are different from each other as depicted by the different lengths of lines J-K versus N-O. Here, we show the impact variable on the y axis returning to a predisaster level; hence, for simplicity reasons it does not include changes in exposure.

"Natech" *(Natural-Technological)* events; see Box 2) (Girgin et al., 2019). Although we focus in this article on natural hazards triggering other natural hazards, the significance of cascading impacts generating new hazards and risk through technological failures should not be ignored. Another type of dependent process is that of *catalysis or impedance relationships*, such as a tropical storm induced flooding where other anthropogenic processes can catalyze the triggering relationships between two natural hazards (Gill & Malamud, 2016). An example of the latter is increased urbanization or infrastructure failures (e.g., blocked drainage systems) increasing the damages due to a tropical storm triggered flooding.

This hazard interaction typology does not capture *compound* events. Compound weather and climate events are defined as a combination of multiple drivers and/or hazards that contribute to risk (Leonard et al., 2014; Zscheischler et al., 2018). This was for example the case in the 2014 Californian droughts: The precipitation deficit was not a record low but its coincidence with substantially higher temperatures and heatwaves did create an extreme event (AghaKouchak et al., 2014). Hence, compound events can include two or more different hazards that have the same climatic driver, such as a heatwave causing both droughts and wildfires (Zscheischler et al., 2018).

Box 2 : Natural-Technological (NATECH) events

Natech disasters are a type of *cascading events* and are commonly defined as natural hazards triggering *technological* hazards (Marzo et al., 2015; Showalter & Myers, 1992). A well-known example of a Natech event is the Great Tohoku earthquake that hit Japan in 2011, which together with a subsequent tsunami caused the Fukishima nuclear reactor meltdown (Nascimento & Alencar, 2016; Peduzzi, 2019). Another example from the same event is that of the two Fujinuma Dams, which failed as a result of the Great Tohoku earthquake, and subsequently caused flooding (Pradel et al. 2013). With regards to Natech events, emergency responders are often not well-equipped nor trained to cope with consecutive or concurrent disasters (Girgin et al., 2019; Steinberg et al., 2008). Many DRR and DRM frameworks fail to include Natech risk (Girgin et al., 2019; Necci et al., 2018). At an international level, some regulations have started to include Natech events, such as the EU 2012/18 directive on the control of major-accident hazards involving dangerous substances (Directive, 2012). Nonetheless, there continues to be a lack in comprehensive local and national scale risk assessments that include both natural and Natech risk (Girgin et al., 2019). In the EU, member states were encouraged to conduct National Risk Assessments (NRAs), and while Natech risk was not considered in a systematic approach, some countries did recognize the relation between the increased potential of Natech events and their impacts, and the effects of climate change (EC, 2017). One approach to assess the risk of cascading impacts of Natech events is through *scenario analysis* (Girgin et al., 2019), where the risk of the most representative combinations of hazard interactions is calculated (Marzocchi et al., 2012). However, the scenario-based analysis still does not fully capture the possibly complex picture of consecutive disasters and will be very difficult – if not impossible – to apply to a global scale risk analysis.

2.2. Causes

The literature recognizes different drivers of disaster, the interconnectedness of which characterizes the complex nature of risk (Cutter et al., 2015; Peduzzi, 2019; Pescaroli et al., 2018; Pescaroli & Alexander, 2015). We discuss these drivers based on the three components of risk.

Historically, the number of recorded disasters caused by natural hazards has more than doubled since 1980 (Cutter et al., 2015). Climate change is widely recognized as an important cause of the increased frequency and intensity of nontectonic hazards as, through changes in thermodynamics, warmer air will increase evaporation and atmospheric moisture content (Dilley et al., 2005; Emori & Brown, 2005; Forzieri et al., 2016; Gallina et al., 2016; IPCC, 2014; Mann et al., 2017; Mora et al., 2018; Papalexiou & Montanari, 2019; Peduzzi, 2019). Mora et al. (2018) showed that greenhouse gas emissions are a major cause of the intensification of climate hazards (e.g., floods, droughts, and heatwaves). In the Northern Hemisphere, future extreme weather events, especially during the summer, will become more pronounced due to these thermodynamic changes (Coumou et al., 2018; Kornhuber et al., 2019). This has direct effects upon those living in the midlatitudes (Mann et al., 2017, 2018). During the Northern Hemisphere's summer and especially at midlatitudes, changes in the midlatitude Jetstream can cause Rossby waves (also known as meanders in the Jetstream), which in their turn can cause above normal temperatures (Kornhuber et al., 2019). This then contributes to a slowdown or stalling of (extra)tropical cyclones (e.g., Hurricane Harvey and the 2014 Balkans cyclone) (Hall & Kossin, 2019), which subsequently increases rain in the cyclone-affected region (Mann et al., 2017, 2018). These compounding effects can create more extreme weather events with high impacts (Coumou et al., 2018; Kornhuber et al., 2019; Mann et al., 2018). Moreover, these Northern Hemisphere summertime standing Rossby waves are likely to become both more frequent and persistent

leading to locally more persistent extreme weather conditions (Kornhuber et al., 2019; Mann et al., 2018). Examples of this are the 2018 extreme weather events in Japan, North America, The Balkans, and Western Europe (Kornhuber et al., 2019; Stadtherr et al., 2016).

As a result, communities exposed to climate-driven hazards are expected to experience more frequent disasters. When integrating to multiple hazard types, this inherently implies a higher chance of interactions that occur over short time frames (Cutter et al., 2015), and therefore more consecutive disasters. It has been shown that global warming is an important cause of the increased chance of concurrent drought and heat-wave events (AghaKouchak et al., 2014). The 2014 and 2018 Californian drought events are prime examples of low precipitation and extreme temperatures causing a range of disasters: Extreme wildfires (during the 2018 event over 1,800 km^2 was scorched and 300 homes were destroyed), precipitation deficits, damaged soils (which in its turn increase the vulnerability to landslides and flooding; Moftakhari & AghaKouchak, 2019), and decreased wintertime water storage (AghaKouchak et al., 2014, 2018). When combining the patterns of changes for all climate hazards, the largest co-occurrence of change is projected to concentrate in the coastal tropical regions (Mora et al., 2018). In coastal regions, climate change is likely to affect sea level rise, which in its turn can affect the likelihood of compound hazards (Moftakhari et al., 2017; Wahl et al., 2015). Many of these regions happen to coincide with active seismic zones, such as the so-called Ring of Fire, as earthquakes and volcanic eruptions tend to occur more frequently in the proximity of coastal zones as they emerge at the boundaries of tectonic plates (Kron, 2013; Terry & Goff, 2012).

Many communities face an increasing risk of multiple disasters due to growing exposure driven by socioeconomic processes such as urbanization and the interconnectedness of human society (Cutter et al., 2015). The dynamic nature of exposure and vulnerability as causes of damages from consecutive disasters is even less understood than that of hazard (Formetta & Feyen, 2019a; Smith et al., 2019). Moreover, DRM still often fails to address drivers of increasing exposure and vulnerability such as uncontrolled urbanization in high-risk locations (Keating et al., 2017). Peduzzi (2019) discusses how disaster risk can be perceived as a dynamic compound event caused in large part by anthropogenic actions and is linked to global change. For example, the relocation of communities from the flanks of a volcano may *decrease* their exposure to volcanic hazards but *increase* their exposure to other hazards, such as floods. Earthquakes can damage and weaken physical infrastructure and therefore increase its vulnerability to future hazards. It has been shown that the increased interconnectivity of infrastructural networks makes it more vulnerable (Sun et al., 2019). The dynamic nature of exposure and vulnerability can therefore result in specific challenges to DRR in contexts where hazards occur consecutively. Only a very limited number of studies have tried to include changes in social and physical vulnerability, for example, through networked risk analysis (Clark-Ginsberg et al., 2018; Gill & Malamud, 2016; Jongman et al., 2015). This underscores the increasing need for a shift to a holistic paradigm of risk and risk reduction (Peduzzi, 2019).

2.3. Occurrences

As a first-order example to illustrate the scope of the consecutive disasters problem, this is illustrated in Figure 3, in this case for tropical cyclones and earthquakes. We use earthquakes and tropical cyclones due to the availability of historic empirical events data (going back until 1960), which has been cited often, and because the two hazards do not have the same drivers, to the best of our knowledge. In Figure 3, we present the total number of consecutive earthquake and tropical cyclone events that occurred within a time window of 3 or 30 days, based on observations from 1960 to 2016 at any given administrative Level 2 area (GADM, 2018). These successions of events can consist of tropical cyclones only (backward slanted lines, \\), earthquakes only (forward slanted lines, //) or both disaster types hitting the same area (dotted) (Figure 3). We generated footprints of tropical cyclones when these were either classed as tropical storms or higher intensity by applying a buffer of 80 km both sides from the track, as applied in Tate et al. (2010), using the IBTrACS data set v03r10 (Knapp et al., 2010). For earthquakes, we considered areas subjected to a Modified Mercalli Intensity Category VIII or higher using a circular radius dependent on the earthquake moment magnitude recorded by the U.S. Geological Survey (USGS) Comprehensive Earthquake Catalog (U.S. Geological Survey, 2017). This relationship was derived based on the analysis of 6,320 raster files (USGS ShakeMap) produced by USGS for earthquakes with a moment magnitude of at least 5. The spatial footprints for each tropical cyclone and earthquake event were intersected with administrative boundaries from GADM (2018).
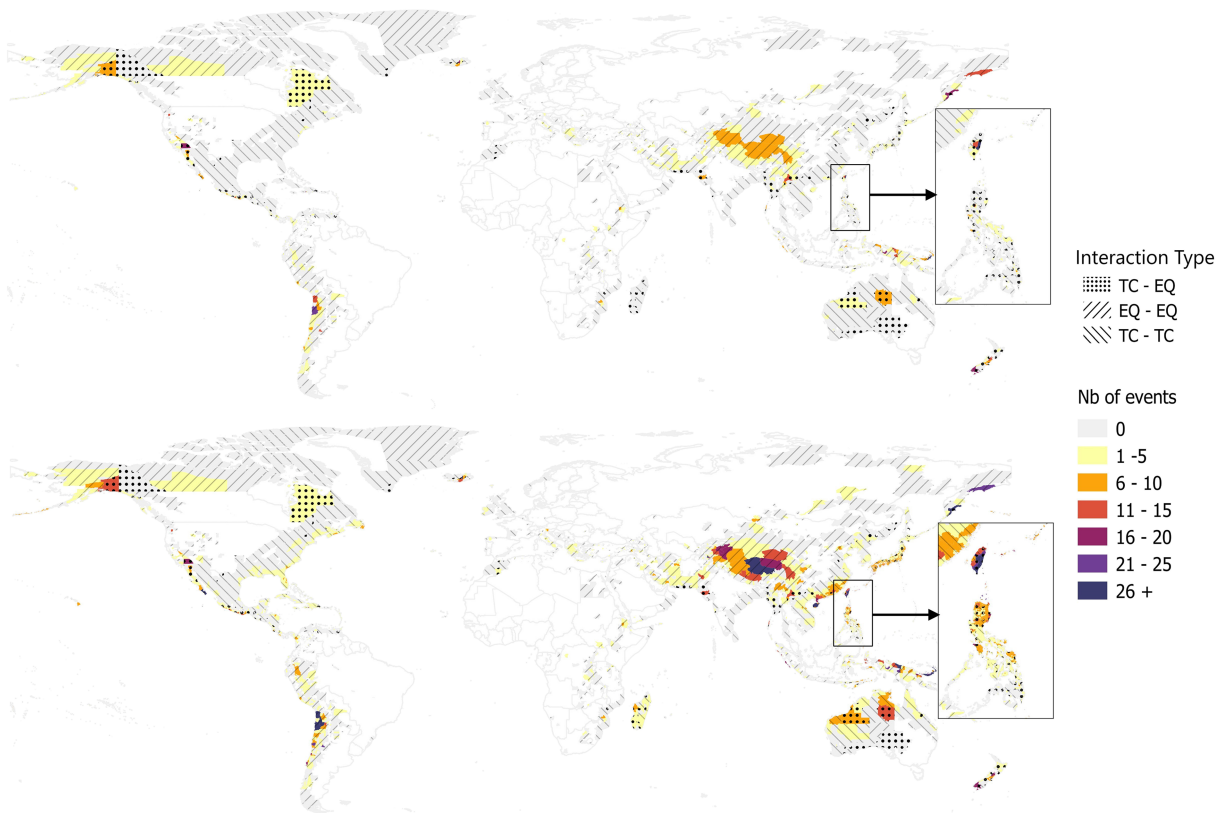
Figure 3. Total number of consecutive events considering earthquake (EQ) and tropical cyclone (TC) interactions. Colored Administrative 2 areas denote regions where at least one EQ or at least one TC has occurred within the period from 1960 until 2016. The top panel shows the total number of consecutive events occurring within a 3-day time window of each other, and the bottom panel uses a 30-day time window. The insets show details for the Philippines and Taiwan.

Areas exposed to strong tropical cyclone and/or earthquake activity, such as the Philippines and Taiwan, show a high number of consecutive events occurring within a 30-day window of each other (see inset in Figure 3), which is still a short timespan for recovery operations. In Figure 3, a similar number of total consecutive events might not necessarily reflect a similar strength in multihazard interactions. We use the total number of events observed for every administrative Level 2 area to provide the relative frequency of these occurrences (Figure S1 in the supporting information) while acknowledging that this empirical probability is particularly uncertain in regions with low tropical cyclone or earthquake activity (Figure S2). Approximately 800 million people face a relative frequency of 20% or more of experiencing more than one disaster within a time window of 30 days (Figure S3). This corresponds to about 10% of the global population.

Next, we focus on the Philippines and the eruption of Mount Pinatubo to highlight the temporal dynamics of multiple hazard interactions. Figure 4 presents the occurrence of tropical cyclones and earthquakes from the data set for a district in the Zambales region where the stratovolcano is located. We add two additional types of hazards, flood events obtained from the Dartmouth Flood Observatory (Brakenridge & Anderson, 2004) and volcanic eruptions from the Smithsonian database (Global Volcanism Program, 2013).

The 3-month-long eruption of Mount Pinatubo in 1991 coincided with the occurrence of a large earthquake, the passage of tropical cyclone Yunya and a flood event. While the earthquake can be linked to the eruption (Jones et al., 2001) the occurrence of the tropical cyclone is completely independent from these two hazards. Yet, because the eruption happened during the typhoon season, the impacts of these series of events aligned to create consecutive disasters. The intense rainfall brought by the tropical cyclone triggered lahars. More than 2 million people were displaced, 8,000 houses were damaged, and more than 300 casualties were reported. This example highlights the importance of considering spatial and temporal dynamics in risk modeling and the recovery process.
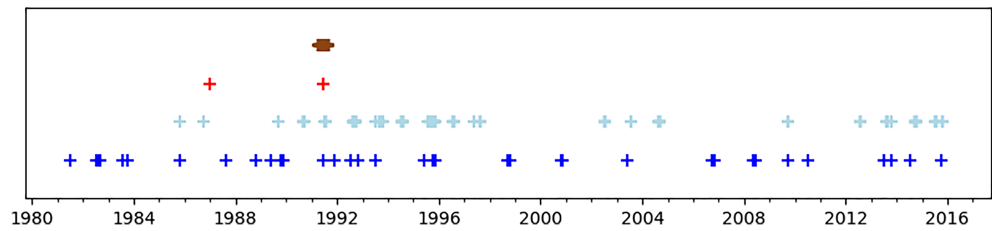
Figure 4. Hazardous events for the Zambales district in the Philippines. Crosses indicate that the district is impacted by an event with the color referring to a tropical cyclone (blue), a reported flood (light blue), an earthquake (red), and a volcanic eruption (brown). The 1991 volcanic eruption refers to the eruption of Mount Pinatubo, one of the biggest eruptions in the twentieth century. The event was accompanied by a major earthquake and coincided with the passage of Typhoon Yunya, which triggered lahars and caused floods. DFO data are available from 1980 onward and only includes flood events that caused damages or losses to humans.

2.4. Impacts

Increasing hazard frequencies and intensities, together with increased exposure and vulnerability of people and assets (IPCC, 2014), have contributed to aggravated risk and resultant global economic losses (di Baldassarre et al., 2018; Wallemacq & House, 2018). Extreme weather events and their impacts are intensifying especially in the world's major breadbasket regions (Coumou et al., 2018). These are located in the midlatitudes where many crop types are vulnerable to extreme heat, and the global food production is therefore facing increasing risk (Coumou et al., 2018). To address this, there is a need to increase understanding of the changing nature of hazards at all levels, from individuals to scientists, to policy makers (AghaKouchak et al., 2018; Cutter et al., 2015; Mora et al., 2018; Peduzzi, 2019).

The impact of a disaster can be measured through different indicators that represent losses and damages (Birkmann, 2007; De Ruiter et al., 2017). Losses are often considered to be irreversible, such as casualties, while damages are considered to be reversible impacts such as injuries and building damages (Mechler & Schinko, 2016). The selection of indicators can have substantial effects on our understanding of the impacts of an event. Insured losses are commonly measured through the number and extent of damaged property (Kunreuther & Pauly, 2006). Hence, an earthquake can cause a large number of buildings to be destroyed, which cannot sustain any more damage during a subsequent disaster if the time window between the two disasters is short enough to not allow for rebuilding after the first disaster. Conversely, an aid organization that uses the well-being of people as an indicator may find that people are actually worse off and more exposed after the earthquake, making them more vulnerable during a second disaster. Both human and aid resources are limited and can be depleted after the first event, aggravating the first response and recovery, which in turn influences the vulnerability at the time of the second event. For example, in Tasmania, first responders' resources were compromised after the late January 2016 flooding, challenging the response to the February wildfires (Hobday et al., 2016).

The impacts of consecutive disasters can be substantial and greater than the sum of its parts (Kappes et al., 2012; Marzocchi et al., 2012), and the impacts of a second event can be larger than that of a first event (see Figures 2 and 5), as demonstrated by the case of the Fukushima disaster caused by the Great Tohoku earthquake: The overall consequences of the triggered event (the nuclear accident) are often considered to be far worse than those of the triggers (the earthquake and the tsunami) (Nagamatsu et al., 2011; Peduzzi, 2019). However, the impacts strongly depend on the metric considered: The vast majority of fatalities (92.5%) occurred as a result of drowning due to the tsunami that followed the earthquake (Nagamatsu et al., 2011). Few studies assess this nonlinearity of the impacts of consecutive disasters at different spatial and/or temporal scales (Budimir et al., 2014; Kappes et al., 2012). In a study of historic earthquake losses, Daniell et al. (2017) set out to attribute historic fatalities and economic losses to earthquakes and the triggered events such as fires, tsunamis, and landslides. The study found that the 100 most damaging earthquakes since 1900 account for 93% of all earthquake fatalities occurring since 1900 and that 40% of the fatalities and economic losses can be attributed to secondary events such as landslides and tsunamis caused by these earthquakes (Daniell et al., 2017). Finally, the literature recognizes the growing need to better understand the vulnerability of ecosystems to a succession of (climate-driven) disasters, such as the impacts of the 2016 and 2017 heatwaves on the Great Barrier Reef (Hughes et al., 2019).

Figure 5. Different dimensions of impact: spatial dynamics (artwork by Henk de Boer©). Schematic representation of spatial changes in exposure and vulnerability due to consecutive disasters. The left panel depicts the predisaster situation where in the front, a large city is located near two rivers and in the background, there is a small-town village in the mountains. In the middle panel, a flood hits the large city and people flee toward the small town in the mountains where they are forced to live in tents. The floods have caused slope instability and subsequently a landslide struck the refugee camp in the mountains, as shown in the right panel. The refugees in the tents are more vulnerable to the impacts of the landslide compared to those living in houses. Finally, because humanitarian resources were deployed toward the large city directly after the flood, which were subsequently depleted, there are fewer resources available to assist the victims of the landslide.

Even when there is no *direct* spatial overlap between different events, indirect impacts can extend far beyond the immediate disaster-struck area (Koks, 2018; Koks et al., 2015; Otto et al., 2017; Poledna et al., 2018; Serinaldi et al., 2018). Poledna et al. (2018) use an Agent Based Model to estimate the indirect economic impacts of disasters over time and find that large-scale events can briefly boost the economy at the short to medium term, although in the long run they will have negative economic impacts. In light of the growing frequency of consecutive disasters, the EU advises its member states to conduct risk assessments not only at time scales that reflect the immediate postdisaster response but include long-term hazard (driver) trends and the impacts of DRR measures (EC., 2017). Please note that we use the term "DRR measures" in abroad sense, and it can therefore include climate adaptation measures. Finally, there are still gaps in our ability to predict the long term impacts of re-occurring extreme weather events on changing migration patterns (Wang & Taylor, 2016), the spread of infectious diseases, for example, through vectors that are transmitted via outside hosts such as ticks or mosquitos (Wu et al., 2016), and on the feedbacks between the occurrence of consecutive disasters and conflicts (Mach et al., 2019; Schleussner et al., 2016; Xu et al., 2016).

3. Consecutive Risk Modeling

Although hazard studies still predominantly focus on single hazards and are limited in terms of temporal and spatial dynamics (Duncan et al., 2016; Gall et al., 2011; Kappes et al., 2012), there is a growing body of multihazard/risk assessment related publications (Kappes et al., 2012), exploring different components of this field. Some selected examples are shown in Table 1. There is a general recognition that the modeling of multihazard risk needs to improve, incorporating changes in exposure and vulnerability to understand dynamic risk and how risk can be reduced (Chang et al., 2018; Formetta & Feyen, 2019b; Mignan et al., 2014), and integrating societal processes (Weichselgartner & Pigeon, 2015). What sets consecutive risk assessments apart from assessments where hazards or disasters are treated in isolation are (1) their spatial dynamics, (2) temporal dynamics, and (3) the need for a cross-hazard comparable method to measure impacts. Some studies have focused on characterizing the potential relationships or dependencies between natural hazards (e.g., Gill & Malamud, 2014), whereas others have set out probabilistic methods to understand potential multihazard risk scenarios (e.g., Mignan et al., 2014). In the literature, many challenges in assessing multiple, consecutive, interacting or cascading risks have been discussed (Duncan et al., 2016; Gill & Malamud, 2016; Kappes et al., 2012; Liu et al., 2015; Marzocchi et al., 2012). Here we provide a brief overview of the state-of-the-art in consecutive risk modeling and discuss the existing challenges.

3.1. Spatial Dynamics

Generally, multihazard risk assessments are studied based on the *spatial* overlap between the risk of different hazard types as faced by one particular geographical area and the *thematic clustering* of hazards (Kappes et al., 2012). This focus on spatial overlap is discussed in different multihazard risk studies (e.g., Hewitt & Burton, 1971; Kappes et al., 2011) and reflected by the typical focus on local-scale case studies

Table 1
Selected Examples of Literature Covering Different Aspects of Consecutive Disasters

Component/aspect(s)	Reference	Brief study description
Hazard		
Hazard dependencies	(Gill & Malamud, 2014)	Characterization of dependencies between different types of natural hazard.
Probabilistic hazard interactions	(Mignan et al., 2014)	Probabilistic methods to assess multihazard scenarios.
Statistical hazard interactions	(Selva, 2013)	Statistical assessment of hazard interactions on risk
Statistical weather-driven hazard interactions	(Hillier et al., 2015)	Statistical assessment of weather-driven hazard interactions and their monetary damages.
Exposure		
Future exposure and future multihazard risk	(Chang et al., 2018)	Accounting for changing exposure and future multirisk.
Vulnerability		
Vulnerability	(Gill & Malamud, 2016)	Changing vulnerability over time due to consecutive events.
Infrastructure	(Fereshtehnejad & Shafieezadeh, 2018)	Infrastructure lifecycle costs and changing vulnerability analysis of infrastructure affected by consecutive disasters.
Buildings	(Korswagen et al., 2019)	Probabilistic assessment of structural damages due to consecutive disasters.
Changing vulnerability curves	(Reed et al., 2016)	Lifeline fragility curves for multiple hazards and hazard interactions based on a statistical approach.
Resilience		
Multievent resilience	(Zobel & Khansa, 2014)	A quantitative measure of resilience in the presence of multiple related sudden-onset disasters.
Resilience	(Keating et al., 2017)	Measure of disaster resilience over time.
Response		
Compromised resources	(Hobday et al., 2016)	Tasmania, first responders' resources were compromised after the late January 2016 flooding, challenging the response to the February wildfires.
Impacts		
Nonlinearity of impacts	(Budimir et al., 2014)	A multivariate statistical approach to assess the nonlinearity of impacts of earthquakes and earthquake induced landslides.
Impact attribution	(Daniell et al., 2017)	Attribution of fatalities due to earthquakes and their secondary effects.
Economic losses	(Moftakhari et al., 2017)	Assessment of the cumulative costs of frequent events for coastal cities in the United States.

(e.g., Grünthal et al., 2006; Marzocchi et al., 2012) or on single elements such as potential dike failure due to floods and earthquakes (Tyagunov et al., 2018) and specific infrastructure systems prone to multitype hazards or multioccurrence of a single hazard type (Fereshtehnejad & Shafieezadeh, 2018). In large-scale multirisk assessment tools, such as the EU's ARMONIA, different hazard types can be spatially overlaid, but the hazards are treated as being independent from each other (Gallina et al., 2016). Understanding the direct and indirect impacts of consecutive disasters requires detailed exposure data. Development and humanitarian organizations do collect impact or needs data, but these are often project or intervention based, hence very local and incidental, and these heterogenous data are therefore not directly usable for research purposes. Van den Homberg and McQuistan (2019) provide an overview of the loss and damage reporting in key global agreements such as the SFDRR and the Paris Agreement and show that the reporting is still done at a very high spatial level. Some studies have created spatially detailed exposure data, but this continues to be temporally static (Smith et al., 2019; Tiecke et al., 2017).

3.2. Temporal Dynamics

The temporal aspect takes into account how changes over time between two disasters influence the damage potential at the time of a second disaster. The temporal aspect has been studied to a much lesser extent and only in more recent years (Chang et al., 2018; Selva, 2013). Most risk assessments assume that the probability of failure of a system (e.g., the building stock) is not compromised by an earlier event (Selva, 2013). Only very few studies (e.g., Korswagen et al., 2019; Lee & Rosowsky, 2006; Yeo & Cornell, 2005) have tried to include the additive effect of a second event in (probabilistic) damage curves or suggest methods to account for this (Kappes et al., 2012). This is even the case for single-hazard assessments as, for instance, the duration of a flood event is currently rarely accounted for in major flood risk studies despite its importance for

assessing indirect losses (Ward et al., 2016). Due to their interactions, if more than one hazard impacts the same area within a short enough timespan, one would expect both the risk and impacts to be different from the sum of their individual components (Kappes et al., 2010; Tarvainen et al., 2006). On the short term, vulnerability is likely to increase at the time of a second disaster due to the direct impacts of the first disaster (Goebel et al., 2015; Kappes et al., 2011). On a longer time scale, vulnerability could decrease rather than increase due to the implementation of DRR measures or raised preparedness levels (di Baldassarre, Nohrstedt, et al., 2018; Formetta & Feyen, 2019b; Marzocchi et al., 2012), such as those proposed by the Build Back Better-framework (Mannakkara & Wilkinson, 2014).

The European Commission Joint Research Centre's INFORM risk index, for example, accounts for the relative number of people affected by shocks in the past three years, scaling down the number with 0.5 and 0.25 for the second year and third year as it assumes that vulnerability decreases progressively through recovery (JRC, 2015). Yet, despite the recognition of the importance of this aspect (Fraser et al., 2016), very little research has been carried out (di Baldassarre, Nohrstedt, et al., 2018), maybe due to its complexity. This underscores the need for risk frameworks and models to include temporal dynamics as an explicit component (2017), such as in Agent Based Models (Aerts et al., 2018; Haer et al., 2019). This also calls for data sets to include exposure dynamics, such as migration (Wang & Taylor, 2016) or DRR measures (Berrang-Ford et al., 2019; Scussolini et al., 2016), a component often lacking in most advanced data sets (EC., 2017).

Selecting an appropriate temporal resolution is crucial in capturing different impacts (Gallina et al., 2016) and depends on the user and the spatial scale of the assessment (Gill & Malamud, 2016). The (re)insurance industry typically considers a second disaster to be a new loss occurrence when that second disaster is at least 72 to 168 hr apart from the first, depending on the hazard type, the so-called "hours clause" (Serinaldi et al., 2018). Conversely, the recovery time window considered by local decision makers and postdisaster aid organizations can go up to years (Marzocchi et al., 2012). The consecutive occurrence of disasters also poses extra challenges for governments (EC., 2017) and humanitarian logistics (Baharmand et al., 2017; Ransikarbum & Mason, 2016).

3.3. Accounting for More Than One Risk

Another challenge is that of comparing and combining risk or impact assessments between different hazard types or for multiple events caused by the same hazard type. This requires a standardized unit to measure and cumulate the impacts of different hazard types, which is difficult to define (Kappes et al., 2012; Korswagen et al., 2019; Marzocchi et al., 2012). This challenge stems in large part from hazards typically being studied in a monodisciplinary fashion (Cutter et al., 2015; Kappes et al., 2012; Peduzzi, 2019). The thematic clustering separating the disciplines causes a lack of understanding between different disciplines due to terminology differences (De Ruiter et al., 2017; Marzocchi et al., 2012). For example, tropical cyclones and earthquakes are independent and distinctly different disasters, stemming from different hazard groups (atmospheric and geophysical respectively) and their impacts occur at very different temporal and spatial scales (Gill & Malamud, 2014). As single or univariate hazard risk assessments tend to either significantly overestimate or underestimate risk of compound events (Moftakhari et al., 2019). AghaKouchak et al. (2014) suggest to assess the risk of compound events caused by climatic extremes using a multivariate framework that can account for compound and concurrent events. Tian et al. (2019) developed a novel framework that allows for the assessment of temporal and spatial changes in community multihazards resilience assessment by taking into account the following five aspects: original prehazard conditions, coping capacity, adaptive capability, hazard loss, and exposure.

4. Research and Policy Roadmap

The state-of-the-art within social sciences and governance research has identified the need to improve our scientific understanding of multirisk assessments (Cutter, 2018; Peduzzi, 2019; Scolobig et al., 2017). What characterizes the currently prevailing risk assessment paradigm is that risk is often represented as static, fragmented in terms of hazard types and the focus tends to be on the hazard component rather than the (dynamics of) exposure and vulnerability and does not account for the impacts of DRR measures. Given the global and potentially increasing frequency and gravity of consecutive disasters and their impacts, as a result of both climate change (IPCC, 2018) and changes in exposure and vulnerability, there is a high urgency to recognize the importance to perceive consecutive disasters holistically, rather than as stand-
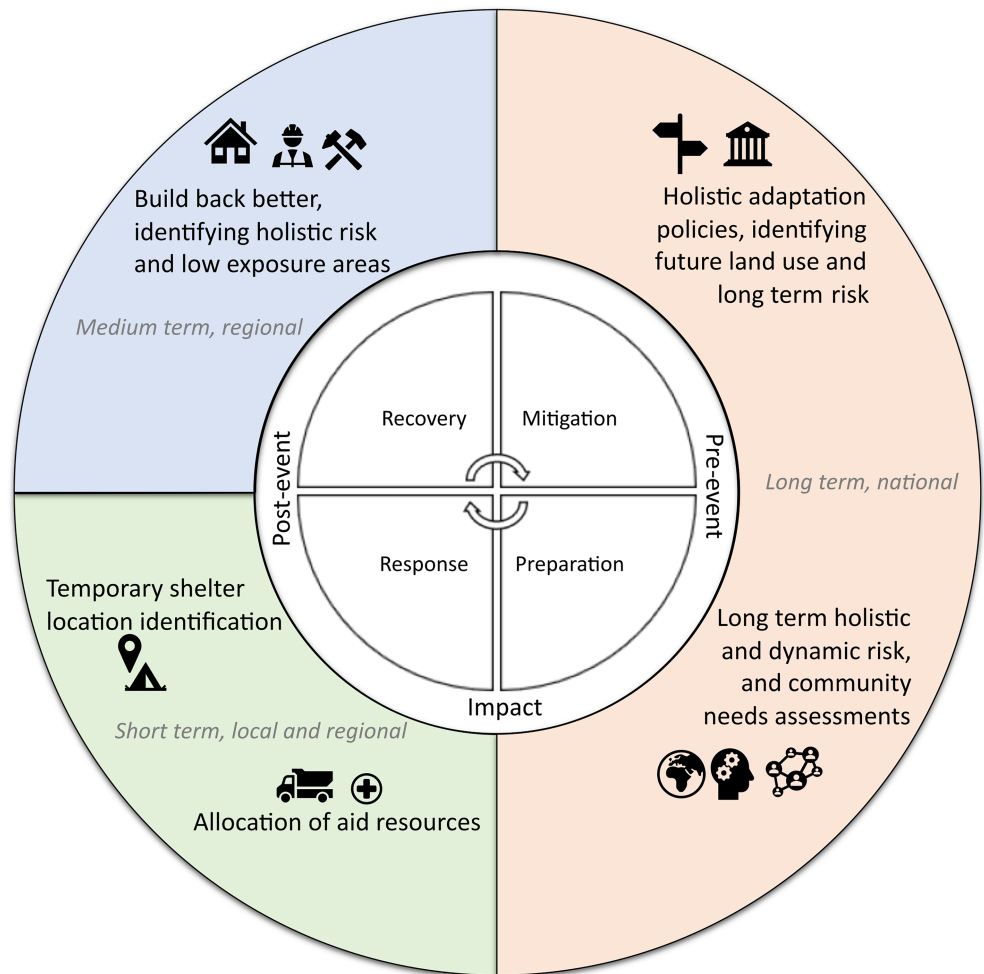
Figure 6. Disaster risk management cycle for consecutive disasters. When accounting for the risk of consecutive disasters, the dynamics of the different risk components should become part of all phases of the DRM cycle. For example, when identifying areas that can be used to set up temporary shelters, people should not be moved to areas at (increased) risk of a consecutive disaster. When developing DRR policies, these should consider not only one prevailing risk but also the risk of consecutive disasters. Background DRM cycle is adapted from UNOCHA (OCHA, 2013).

alone events, acknowledging their complexity and accounting for the interconnectivity of the different drivers of consecutive disasters (Ismail-Zadeh et al., 2017; Peduzzi, 2019). The application of such interdisciplinary system thinking has recently resulted in the launch of the Global Risk Assessment Framework that aims to provide decision makers with actionable insight on how to approach complex systemic risks (Global Risk Assessment Framework, 2019). Figure 6 shows the DRM cycle with the temporal and spatial dynamics of consecutive risk added.

Many challenges in multirisk governance and institutional barriers continue to exist that prevent policy makers from accounting for consecutive risk in DRR planning (Scolobig et al., 2017). In part, these challenges result from insufficient scientific understanding of the complexities of multirisk assessments, hindering the scientific support for decision makers in addressing multirisk (Scolobig et al., 2017). Going forward, we need a paradigm shift to take a holistic view of risk that in its turn enables the development of more sustainable design of DRR measures and holistic risk management policies (Cutter et al., 2015; Peduzzi, 2019; Scolobig et al., 2017). Moreover, owing to the complexities of multihazard risk, the coupling between the generation of multirisk knowledge and multirisk governance needs to be improved. The codesign of policies between policy makers, communities, and scientists allows decision makers to tailor disaster preparedness

policies to local or regional needs and it can help identify how resilience and DRR measures would respond to (the interaction between) different hazard types and consecutive disasters (Weichselgartner & Pigeon, 2015). We therefore outline the following roadmap highlighting key future research and policy directions, and possible ways to strengthen coherent policies for DRR.

- Understanding the spatial and temporal dynamics of consecutive disasters requires large amounts of data on hazards, exposure, vulnerability, and impacts. Data need to be available and standardized across sectors and hazard types, and unlocking high-resolution and novel data such as those obtained through drones, online media, and citizen science should become more mainstream and integrated with other data sources. As data quality and availability improve, consecutive risk assessment models need to be able to incorporate different data sources, hazard interactions, and temporal and spatial dynamics. However, institutional arrangements currently lack the ability to address consecutive disasters during all phases of the DRM cycle. Therefore, more emphasis should be put on transdisciplinary collaborations to enable cross-discipline understanding and the development of multidimensional consecutive risk models that can account for interdependencies between hazards (AghaKouchak et al., 2018).

- Potential adverse effects of DRR measures directed toward one hazard type on other hazard types need to be better understood as recognized in recent literature (e.g. di Baldassarre et al., 2018; Scolobig et al., 2017) and reflected in subsequent cost and benefit analysis (e.g., Hochrainer-Stigler et al., 2010; Kull et al., 2013). This is in part due to the fragmentation of scientific knowledge and a lack of coproduction of knowledge with stakeholders such as policy makers (Ismail-Zadeh et al., 2017). A coherent and integrated approach for creating DRR to support policy and decision makers is required and should be informed by a body of transdisciplinary, international DRR experts (Cutter et al., 2015; Scolobig et al., 2017).

- Currently, disaster management and humanitarian aid logistics tend to focus on the short-term impacts of a disaster. Especially due to the dynamic nature of consecutive risk, risk frameworks and subsequent DRR policy need to be increasingly holistic, include long-term planning and indirect impacts. Due to the dynamic nature of consecutive disasters, disaster governance takes place at different stages of the DRM cycle (Blair et al., 2018) as reflected in Figure 6, with the response and recovery phases of postdisaster operations least understood (Ransikarbum & Mason, 2016). Accounting for more than one hazard type would force decision makers to include long-term planning and could allow them to tailor risk reduction measures accordingly (Durham, 2003) and develop more effective urban planning policies (Peduzzi, 2019; Scolobig et al., 2017). Damage attribution studies may help in this regard by providing decision makers with information about the relative importance of different drivers on damage, thereby helping to direct risk reduction investments. Both large- and local-scale approaches are required and the possibility to scale between them should be improved to create a more comprehensive understanding of the local impacts of consecutive disasters, thereby including indirect impacts. Generally, indirect impacts should be better accounted for, and the lag time for indirect impacts to become visible should be incorporated in models.

- We need to critically rethink the indicators used to measure impacts in different contexts, and how this can enable an increased understanding of the dynamics of risk and impacts. The impact data that are collected by governmental stakeholders (including first responders), international and humanitarian organizations, and researchers from different fields are very heterogenous (AghaKouchak et al., 2018; Cutter et al., 2015; Weichselgartner & Pigeon, 2015) and often collected at different times after the disaster hits (van den Homberg et al., 2018). A standardization of data facilitates coupling between models and would allow for better modeling of consecutive risk. Some attempts have been made. For example, the UN's Inter-Agency Standing Committee has provided guidelines to the humanitarian sector for coordinated impact assessments (Inter-Agency Standing Committee, 2012) and the World Meteorological Organisation has started a pilot project to systematically catalogue hazard information of hydrometeorological events allowing for a unique matching with other loss and damage databases (WMO, 2018). Despite these coordination guidelines and efforts, usually there is still a plethora of assessments reports (Van den Homberg et al., 2014). Moreover, the guidelines are developed for typical sudden onset disasters; no specific adaptations are known for consecutive disasters. As accounting for consecutive disasters brings with it the challenge of attributing damages, it would benefit greatly from a clear typology of impact indictors.

- Finally, data sets are usually not freely accessible as they tend to be protected by nondisclosure agreements (Gall et al., 2011; Weichselgartner & Pigeon, 2015). An increased collaboration between researchers, first responders, and institutes and companies collecting data could increase data availability for

research and early response purposes (van den Homberg et al., 2018; Weichselgartner & Pigeon, 2015). Improved data availability and quality enables benchmarking, which is crucial for assessing disaster resilience over time (Keating et al., 2017). Similarly, an improved knowledge transfer and codesign of DRR contribute to community-level resilience (Cutter et al., 2015).

5. Conclusions

We provide an overview of the state-of-the-art in the understanding of consecutive disasters as discussed in the literature. We outlined the different types of consecutive disasters, their causes, and impacts. Existing empirical earthquake and tropical cyclone disaster databases were used to demonstrate the global probabilistic occurrence of these hazard types. The impacts of consecutive disasters can be distinctly different from single hazards, and their prevalence is increasing due to climate change and increasing socioeconomic exposure and consecutive disaster vulnerability. We identified the knowledge gaps based on our review of consecutive risk assessments and made suggestions for improvements that can benefit stakeholders at various spatial scales such as policy makers, urban planners, first aid responders, and disaster recovery agencies, as well as (re)insurance and financial industry. However, identifying the current modeling gaps is only one part of the problem. Even with perfect consecutive disaster modeling capabilities, the current institutional arrangements continue to lack the ability to address consecutive disasters during all phases of the DRM cycle (i.e., developing preventive policies, early action response plans, etc.). To better address consecutive disasters, from a modeling as well as from a policy perspective, requires a more holistic approach to DRM.

Data Availability Statement

The data set created for the global past consecutive earthquake and tropical cyclone disasters at administrative boundaries Level 2 are freely available online using Harvard University's data archive software "DataverseNL" (https://dataverse.nl/dataset.xhtml?persistentId=hdl:10411/NYLQWW). Population Density Data were obtained from NASA's Socioeconomic Data and Applications Center (SEDAC) open access GWPv4 database; GWPv4 contains globally gridded population data for every 5 years between 2000 and 2020 (Center for International Earth Science Information Network-CIESIN-Columbia University, 2018). Reported flood events and volcanic eruption data used for Figure 4 were obtained from the Dartmouth Flood Observatory and the Smithsonian database.

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