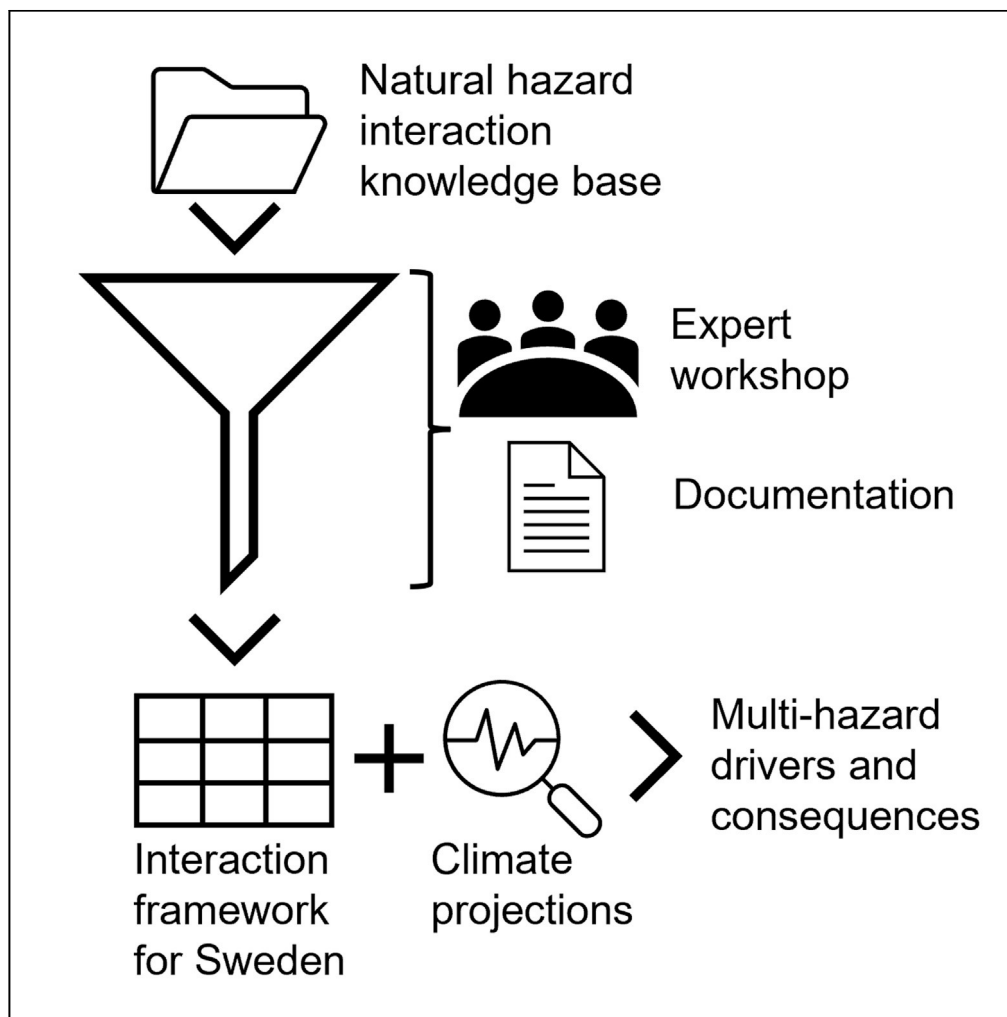


Article

Construction of a national natural hazard interaction framework: The case of Sweden



Viktor Sköld
Gustafsson,
Mattias Hjerpe,
Gustav
Strandberg

viktor.skold.gustafsson@liu.se

Highlights

We found evidence for interactions between 77 natural hazard pairs in Sweden

The interactions were classified into four different interaction types

Almost all hazards examined had interactions as both a primary and secondary hazard

Heat wave and heavy rain will increasingly trigger and drive hazards in Sweden

Sköld Gustafsson et al.,
iScience 26, 106501
April 21, 2023 © 2023 The
Author(s).
<https://doi.org/10.1016/j.isci.2023.106501>



Article

Construction of a national natural hazard interaction framework: The case of Sweden

Viktor Sköld Gustafsson,^{1,4,*} Mattias Hjerpe,² and Gustav Strandberg³

SUMMARY

Recent multiple natural hazards and compound climate events studies have identified a range of interaction types and examined natural hazard interactions in various locations. Yet, there are calls for examining relevant multiple natural hazards in still unstudied national contexts as Sweden. Moreover, multi-hazard concepts rarely consider climate change effects, despite the call of the Intergovernmental Panel on Climate Change (IPCC) to adopt multi-hazard approaches and the growing recognition that compound events should be considered “normal”. Using a systematic literature study, the paper presents a national natural hazard interaction framework for Sweden identifying 39 cascading, 56 disposition alteration, 3 additional hazard potential, and 17 coincident triggering interactions between 20 natural hazards. Reviewed gray literature, an expert workshop, and reviewed climate research suggest increases of multiple natural hazards with heat wave and heavy rain as triggering or driving events and with hydrological hazards, for instance, fluvial floods, landslides, and debris flows, as the main consequences.

INTRODUCTION

Natural hazard¹ and climate change research^{2,3} increasingly recognize that natural events interact. Calling for more studies on multi-hazards, the Sendai Framework⁴ and Ward et al.⁵ point to the need for studies examining the most relevant multiple natural hazards in different national and subnational contexts. Likewise, research on compound climate events that can be understood as “the combination of multiple drivers and/or hazards that contributes to societal or environmental risk” argues for more studies on interactions.³ Still, conventional analyses of climate and weather extremes^{2,3,6,7} and multi-hazard studies^{5,8} generally tend to focus on single variables or individual hazards, with some exceptions (e.g., Simpson et al.⁹). Furthermore, despite the increased attention to multi-hazards, they are rarely mainstreamed in disaster risk management.^{5,10}

Reviewing natural hazard interactions studies, Tilloy et al.¹⁰ demonstrate that two fields use either the multi-hazard or the compound concept, with some overlap; the compound concept was frequently used in climate hazard studies, focusing on hydrometeorology, whereas the multi-hazard concept was predominantly used in hazard studies related to solid earth and surface processes. There have been several previous attempts to classify how natural hazards interact.^{1,9–12} A recent literature study-based synthesis by De Angeli et al.⁹ distinguishes between six interaction mechanisms: parallel hazards, cascading hazards, disposition alteration, additional hazard potential, coincident triggering, and cyclic triggering.

Natural hazard interactions have been studied and analyzed previously in different parts of the world: Europe,¹³ Guatemala,¹⁴ the French Alpines,¹⁵ Greece,¹⁶ Italy,¹⁰ and the Yangtze river delta in China.¹² However, they can only partly inform on the issue of natural hazard interactions in another region since the collection and synthesis of evidence in the studied region are necessary to enable regional interaction analyses.¹⁴ To our knowledge, no such study has examined multiple natural hazards for Swedish conditions. Sweden has adopted the multilateral Sendai Framework for Disaster Risk Reduction, explicitly pointing to the need for multi-hazard approaches.⁴ Hence, there is a need for multi-hazard analyses based on the Swedish environmental setting to inform the preparedness and response to such events.^{14,17} Accordingly, this study will zoom in on the Swedish case using a similar approach as that of Gill et al.¹⁴ in an exploratory way, which is promising in such under-explored areas.¹⁸

¹Department of Science and Technology, Linköping University, SE-601 74 Norrköping, Sweden

²Department of Thematic Studies; Environmental Change and the Centre for Climate Science and Policy Research, Linköping University, SE-581 83 Linköping, Sweden

³Rosby Centre, Swedish Meteorological and Hydrological Institute, SMHI, Norrköping SE-602 19, Sweden

⁴Lead contact

*Correspondence: viktor.skold.gustafsson@liu.se

<https://doi.org/10.1016/j.isci.2023.106501>



Moreover, in their review of multi-hazard concepts and tools, Gallina et al.⁸ found that these studies rarely consider the effects of climate change, despite the call of the Intergovernmental Panel on Climate Change (IPCC)¹⁹ to adopt multi-hazard approaches and the growing recognition that compound events should be considered “normal” instead of “exceptional”.²

This study aims at presenting a national natural hazard interaction framework for Swedish conditions. The framework is intended to support decision-makers and analysts in emergency management and spatial planning. To allow for analyses of both current and future conditions, the paper also explores how a subset of “interaction-rich” natural hazards may be influenced by climate change. The research is guided by three research questions:

RQ1: Which multiple natural hazards are viewed as the most relevant for Swedish conditions?

RQ2: In what ways are these relevant multi-hazards described to interact?

RQ3: How is climate change likely to influence a subset of these multiple natural hazards?

This article is structured as follows: section two overviews natural hazard interaction literature and how climate change may affect such interactions. Section three presents the results of this study, regarding both the natural hazards of relevance to Swedish conditions, whether there was any evidence to suggest any type of interaction, and how climate change is likely to influence a subset of the multiple hazard interactions. Section five discusses the results and concludes.

Interactions between natural hazards

This section presents an overview of natural hazard types, different frameworks to describe natural hazard interactions, and how climate change may affect the interactions.

Types of natural hazards

Natural hazards are natural processes or phenomena that may cause health impacts, property damage, economic disruption, or environmental degradation.²⁰ They can be divided into geophysical, atmospheric, hydrological, biophysical, celestial, and shallow earth process events.¹ Geophysical events include earthquakes, tsunamis, volcanic eruption, and landslides.^{1,14} Except for landslides²¹ and landslide-triggered tsunamis, these events are very rare in Sweden.²² Atmospheric events include storm, tornado, hailstorm, lightning, heat waves, and cold spells. Hydrological events include flood and drought, while wildfire is classified as a biophysical event. Celestial or space events include geomagnetic storms and impact events. Shallow earth processes include regional subsidence, ground collapse, soil subsidence, and ground heave.

In this paper, we will use this categorization, with three adjustments. Firstly, biological phenomena, for instance, epidemics and pest infestations, also qualify as natural events²³ and were included as a separate category. Secondly, landslides and shallow earth processes,¹ including slips and subsidence, have been divided into geophysical and hydrological mass movements since they can depend on both geophysical and hydrological circumstances.²⁴ Thirdly, we regrouped different kinds of storms (rain, hail, snow, and tornado) into two separate categories, heavy precipitation and storm (winds, low pressure), to better grasp what elements of a storm potentially lead to specific interactions.

Types of interactions between natural hazards

In their review of the understanding and categorization of interactions and simultaneity between natural events, Tilloy et al.¹¹ noted two fields that use either the multi-hazard or the compound concept. The multi-hazard concept is used mainly within hazard research connected to natural sciences like geophysics and geology, with a focus to understand interactions on hazard level. Attempting to synthesize the growing literature in this field, De Angeli et al.¹⁰ suggests six interaction types or interaction mechanisms between natural hazards: parallel, cascading, disposition alteration, additional hazards potential, coincident triggering, and cyclic triggering. For the compound concept, Zscheischler et al.²⁵ distinguish between four types of events: preconditioned, multivariate, temporally compounding, and spatially compounding. This concept is used within climate and earth system sciences with a focus to understand the climatic preconditions and drivers behind hazards and their interactions and has mainly considered hydrometeorology.¹¹ The general idea of these two categorizations is given in [Figure 1](#).

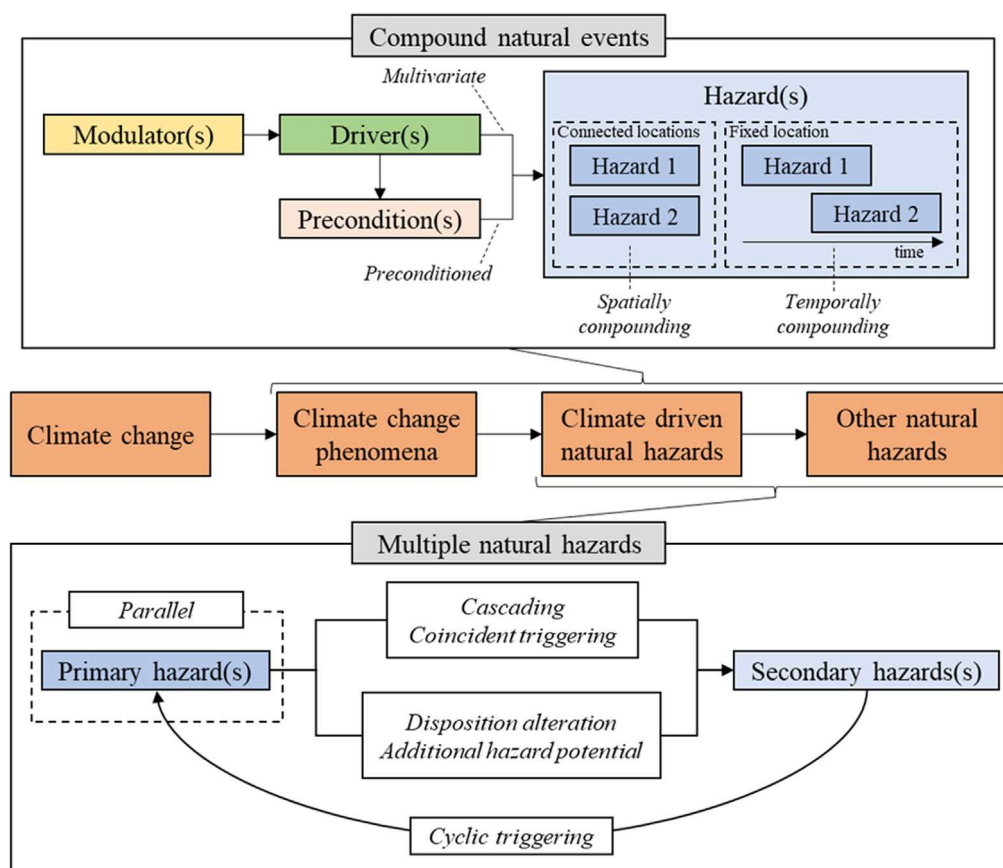


Figure 1. A schematic view of how natural hazards interact in the multiple natural hazards and compound climate events; literature obtained from categorizations in De Angeli et al.¹⁰ and Zscheischler et al.²⁵

A parallel hazard is defined as a series of hazards generated by the same trigger, such as intensive rain triggering both a landslide and a pluvial flood.¹⁰ Cascading hazards occur when one hazard triggers one or more sequential hazards, for instance, an earthquake-induced tsunami.¹¹ Disposition alteration means that a primary hazard influences the magnitude or frequency of a second hazard.¹⁰ The influence does not necessarily have to come from a hazardous event. Here a wildfire could, through vegetation combustion, increase the propensity for a hydrological mass movement. Additional hazard potential is when the damage caused by a primary hazard may affect the magnitude of a secondary hazard.¹⁰ One example is a drought increasing the damage potential of an urban heat wave through decreased tree cover. Coincident triggering implies that two hazards occur simultaneously and together trigger a third one.¹⁰ This is the case when a lightning strikes during a drought and triggers a wildfire. Finally, cyclic triggering is when the triggering of the secondary hazard aggravates the primary hazard and, in turn, triggers further episodes of the secondary hazard, creating positive feedback.¹⁰ In our framework, we will use four of the triggering or preconditioning interaction mechanisms: cascading, disposition alteration, additional hazard potential, and coincident triggering. Parallel hazards, not necessarily involving any triggering or preconditioning, will be presented in section “influence of climate change on future multiple natural hazards” together with the climate change effects. Cyclic triggering events are considered rare and only applicable to a small set of interacting events; hence, it is excluded from further study.

Climate change and interactions between natural hazards

Climate and weather variables are indicators of a range of hazards.² Climate change research has identified that magnitudes, frequencies, return periods, and spatial distribution of different climate variables are already changing and are expected to continue to do so.²⁶ Climate change may alter the duration, frequency, timing, spatial extent, and magnitude of natural hazards. Leonard et al.² emphasize that, since almost all natural hazards are forced by multiple climate variables, these changes increase the complexity

of modeling their expected frequency and magnitude. Changes in climate variables associated with multiple hazards or compound events can sometimes be in opposite directions.² In a multi-hazard context, Gallina et al.⁸ underscore the importance of identifying appropriate climate variables and metrics (e.g., mean, average, cumulative values) used to represent the hazard.

Over the last 100 years the global mean temperature has increased with around 1°C, due to increased amounts of greenhouse gases in the atmosphere.²⁶ Almost all parts of the world have already become warmer, and the continued warming trend is the most robust climate change pattern. This also affects temperature extremes. The frequency and duration of hot extremes mostly increase linearly with each degree of global warming. Some changes in threshold exceedance or frequency are, on the other hand, exponential.²⁷ An increase in hot extremes due to anthropogenic climate change is already observed in northern Europe.²⁶ As climate continues to warm, all kinds of hot extremes will increase.²⁸ This is the strongest signal for Swedish conditions.²⁹ Wilcke et al.³⁰ show that the probability of a hot summer like in 2018 has increased considerably since pre-industrial times. Based on regional climate models, Lin et al.³¹ show a strong increase in the heat wave duration index also over Scandinavia.

There is a strong correlation between droughts and heat waves.³² Globally, increased frequency of concurrent heat and drought events is already observed. As this trend is driven by temperature change, it is expected to continue in the future, even if droughts are not more common.²⁸ Furthermore, there is evidence of larger contrasts between dry and wet years in the Baltic region.²⁹ Also in Europe, compound hot and dry events are already more frequent, with increased probability in most of Europe between the mid and end of the 20th century.³³

Precipitation and wet extremes have already increased in northern Europe,²⁶ as predicted by the Clausius-Clapeyron equations.³⁴ Winter precipitation is very likely to further increase in the future in northern Europe.^{35,36} Regional climate model studies show a projected increase of extreme precipitation already in the coming decades.^{37,38} Important to note is that extreme precipitation is projected to increase also in regions where the mean precipitation is projected to remain unchanged or decrease.²⁸

Globally, compound flooding (storm, extreme precipitation, and/or stream flow) will become more frequent in some areas because of higher levels of water and extreme precipitation.²⁸ In northern Europe, increases in wet extremes are already observed.²⁶ Compound flooding due to increased sea level, extreme precipitation, and runoff is expected to increase along large parts of the European coast.²⁷ The main stream flow signals in Sweden are earlier and decreased snowmelt-induced spring floods, and an increase of precipitation-induced autumn and winter stream flows is projected. There is no single response that describes changes in stream flow. Generally, there is a shift from a snowmelt- to a rain-driven regime, but the response in the individual catchment area depends on how dominating the snowmelt regime is.^{39–41}

Droughts have several definitions; hence, it can be measured differently. Precipitation amount, soil moisture, stream flow, and impact on society are all different measures of drought. Summer droughts in Sweden are usually connected to high-pressure blockings and high temperatures. Summer precipitation in Sweden is not projected to change much,⁴² but there are signs of more frequent dry conditions⁴³; and with increased evaporation, due to increased temperature and a longer vegetation period, soil moisture and stream flow are expected to decrease even with the same amount of precipitation.^{39,44}

The confidence in avalanche projections is low due to short or inhomogeneous observations and models without sufficient resolution.²⁷ In general, both the snow season length and the maximum snow depth have decreased in Scandinavia, with the possible exception of the far north where the maximum snow depth remains constant.²⁹

Fire weather, related to heat and drought, and driven by high temperatures, low soil moisture, and humidity, is projected to increase.⁴⁵ Indicators of fire weather include combinations of temperature, soil moisture, humidity, and wind.²⁷ Although the projected changes of wind are uncertain or small, fire weather is probably becoming more likely in Sweden due to increased temperature and decreased soil moisture, which would lead to more frequent fire weather, especially in the south-east.^{45,46}

Globally, decreased frequency and intensity of cold extremes are observed, and this trend is expected to continue.²⁸ Due to feedback mechanisms connected to decreasing snow and ice cover, the increase in low temperatures is expected to be higher than the increase in mean or high temperatures.^{35,36}

There is low confidence in any observed trends of wind on high latitudes and small expected future changes.²⁸ Over the Baltic region no trends in storm tracks, frequency, or intensity are identified due to large variability.⁴⁷ Reviews of the future wind climate in the Baltic region or northern Europe conclude that the projected trends are small, however, with large uncertainties and low model agreement.^{35,36,48}

Coastal erosion is driven by coastal currents and waves,²⁹ but it also depends on the intensity of storms and could be enhanced by ice-free conditions.⁴⁹ In the Baltic Sea, coastal erosion is most severe on the southwestern coasts of Sweden and Denmark, where sea levels increase the most.

The occurrence of lightning is connected to severe convective storms. However, the low data quality makes it difficult to assess how the balance between the different atmospheric conditions affecting deep convection will affect the lightning frequency. Beneficial dynamical changes may be counteracted by microphysical properties of the clouds, which make it difficult to say whether lightning will be more frequent in Sweden.⁵⁰

RESULTS AND ANALYSIS

This section presents the results of the study, including the natural hazards identified as relevant for Swedish conditions, their interactions, and how climate change will affect the interactions.

Natural hazards relevant in a Swedish context

Based on the review of agency reports and the expert workshop, a set of 12 natural hazards (Table 1) viewed as relevant for Swedish conditions was established divided into five categories: geophysical, atmospheric, hydrological, biophysical, and biological. The following natural hazards and their respective interactions were excluded from further study: earthquakes, tsunamis, volcanic eruptions, and ice storms due to *low historical frequency*; meteorites due to *low historical impact on the Swedish society*; and epidemics and geomagnetic storms due to *no known interactions as a primary hazard*.

The only geophysical mass movements that occur in Sweden are rock falls and rockslides. However, hydrological mass movements are more frequent, with around 40 landslides annually, the majority impacting an area less than one hectare. During the period 2000–2015, Sweden recorded 85 larger landslide events, impacting more than one hectare.⁵¹ Storms are common in Sweden, although hurricanes are rare. Between 1980 and 2010, the number of days with winds above 25 m/s was 15–20 times yearly.⁵² Heavy precipitation, in combination with heavy winds and low pressure, or cloudbursts are quite common, with 2–3 yearly rains at 5.5 + mm/h during at least 6 h in each of Sweden's four weather regions.⁵³ According to Isaksson and Wern,⁵⁴ Sweden had on average 165,000 strokes of lightning annually during the period 2002–2009. Although southern Sweden has a temperate climate, extremely high temperatures are rare with a few occurrences of around 35°C.⁵⁵ Extremely low temperatures are not uncommon in the north of Sweden, with winter temperatures reaching as low as –45°C, but rarer in the south.

Snowmelt- and rain-induced floods are two of the more common natural hazards with impacts on the Swedish society. According to the Swedish Civil Contingencies Agency,⁵⁶ Sweden experienced on average five annual flooding events with adverse impacts on society during 1985–2010. In a recent survey over 2005–2019, Sweden experienced 20 flooding events per year in watercourses and 250 floods per year caused by stormwater and draining system overflows. Periods of drought are uncommon in Sweden but will impact the society when occurring, especially agriculture. Between 1990 and 2018, Sweden had five periods of drought in terms of low or very low groundwater levels, of which three happened during 2016–2018.⁵⁷ Although the annual frequency of avalanches is high in Sweden, 5 000–10 000 during 1915–2016,⁵⁸ they mostly occur in uninhabited areas with limited impact on society and lead to approximately one casualty per year.

Both 2014 and 2018 were two heavy wildfire seasons in Sweden and were challenging for the emergency services.⁵⁹ During 1996–2018, Sweden had close to 2 500 yearly forest fires, of which 32 led to a burnt area larger than 10 ha. The occurrence of grass- and bushfires was about the same.⁶⁰ Pest infestations are increasing in Sweden, especially within forestry, where the population of bark beetles has increased in recent years and caused more than eight million cubic meters of dead spruce.⁶¹

Table 1. Overview and description of natural hazards included in the interaction framework

Category	Natural hazard	Description
Geophysical	Geophysical mass movements	Slides and slips triggered by geophysical activity, such as earthquakes and volcanic hazards.
Atmospheric	Storm	A strong wind has wind speeds above 13,9 m/s. A storm or a hurricane have wind speeds above 24,5 and 32,7 m/s, respectively. ⁶⁴ Low air pressure can generate higher sea levels, which in combination with wind can create storm surges. ⁶⁵
	Heavy precipitation	Constitutes rain, hail, or snow. A rainfall can be classified as heavy when it falls more than 4 mm/h, while a shower (10–20 min) is heavy above 10 mm, and a cloudburst at a total amount of 50 mm or 1 mm/min. ⁶⁶
	Lightning	When the charge difference between two thunderclouds, or between a thundercloud and the ground, gets too large, the isolating effect of the surrounding air is lost. That causes a discharge equalizing the two differing charges, which is called lightning. ⁶⁷
	Heat wave	In temperate climates, such as the Swedish, the temperature varies over the year, creating conditions for both extremely high and low temperatures. ⁵⁵ The terms also include abnormally deviating temperatures, such as freezing temperatures during summer.
	Cold spell	
Hydrological	Flood	Water that covers ground outside normal boundaries of oceans, seas, or watercourses, due to either increased water levels or heavy precipitation. ⁶⁵ Water levels depend on the precipitation, snowmelt, depletion, air pressure, and wind.
	Drought	Drought occurs during periods of low precipitation and high evaporation when watercourses, lakes, and soil are not refilled with water as normal, while the vegetation absorbs the small amount of water available. ⁶⁸
	Hydrological mass movements	Hydrological mass movements occur when water levels rapidly increase or fluctuate within or above the ground ²⁴ and constitute any downslope movement of earth materials ⁶⁵ with hydrological causes.
	Avalanche	The collapse of snow down a slope or a mountain side. There are five types of snow avalanches ⁶⁹ : slab, loose snow, gliding, powder, and wet snow. Out of these, slab avalanches are considered the most dangerous.
Biophysical	Wildfires	Fires in all biomes, ⁶⁵ such as forest, grassland, mire, and moor. Large frequency and size variations depending on weather conditions and soil moisture ⁷⁰ since the fire risk increases in drier environments. ⁷¹
Biological	Pest infestations	The population or the impact from pests reaches unsustainable levels in a limited geographical area, ⁷² such as insects or animals damaging eatables, agriculture, or forestry. ⁷³

Interactions between natural hazards in a Swedish context

Through the reviewed literature, government agency documents, and discussions at the expert workshop, we have set up a national natural hazard interaction framework for Sweden (Figure 2). Starting from the twelve natural hazards presented in Table 1, we further divided the following hazards into subtypes:

- storms were divided into strong wind and low pressure;
- heavy precipitation was split up into heavy rain and snow;
- flood was divided into coastal, fluvial, pluvial, and flash flood; and
- hydrological mass movements were divided into landslide, debris flow, soil movement, and erosion.

The resulting 20x20 natural hazard interaction framework will allow for a more detailed analysis and insights into different kinds of interactions viewed as relevant for Swedish conditions.

			Secondary hazard																			
			RF	ST		HP	LI	HW	EL	FL				DR	HM			AV	WI	PI		
			Rock fall/slide	Strong winds	Low pressure	Heavy rain	Snow	Lightning	Heat wave	Cold spell	Coastal flood	Fluvial flood	Pluvial flood	Flash flood	Drought	Landslide	Debris flow	Soil movement	Erosion	Avalanche	Wildfire	Pest infestation
Primary hazard	RF	Rock fall/slide	 									 										
	ST	Strong winds							 									 		 		
		Low pressure		 																		
	HP	Heavy rain								 	 	 		 	 	 	 		 			
		Snow																	 			
	LI	Lightning																		 		
	HW	Heat wave				 										 	 			 		
	EL	Cold spell																				
	FL	Coastal flood																				
		Fluvial flood													 		 	 				
		Pluvial flood													 		 	 				
		Flash flood													 	 	 	 				
	DR	Drought						 				 									 	
	HM	Landslide													 	 	 					
		Debris flow													 		 					
		Soil movement													 							
Erosion														 	 	 						
AV	Avalanche																		 			
WI	Wildfire						 					 					 					
PI	Pest infestation																					

Geophysical	Rock fall/slide	RF
Atmospheric	Storm	ST
	Heavy precipitation	HP
	Lightning	LI
	Heat wave	HW
	Cold spell	CS
Hydrological	Flood	FL
	Drought	DR
	Hydrological mass movement	HM
	Avalanche	AV
Biophysical	Wildfire	WI
Biological	Pest Infestation	PI

	Cascading
	Disposition alteration
	Additional hazard potential
	Coincident triggering

Figure 2. A Swedish national natural hazard interaction framework

The 20x20 matrix displays primary hazards vertically and secondary hazards horizontally. The interactions include primary hazard triggering a secondary hazard in a cascade (red), primary hazard altering the disposition of a secondary hazard (blue), primary hazard amplifying or increasing the potential of a secondary hazard (yellow), and primary hazard coincidentally triggering a secondary hazard (green). The matrix was populated using the three different evidence types (see also [Tables S1](#) and [S2](#)).

The types of interactions included are the four cascading types described by De Angeli et al. (2022): cascading, disposition alteration, additional hazard potential, and coincident triggering. However, we consider additional hazard potential to also include amplifying effects between natural hazards (i.e., wind leads to more severe wildfires) instead of just a primary hazard's impact on physical elements designed to reduce the risk of secondary hazards.¹⁰ In the workshop, the experts provided examples of multiple hazards in Swedish conditions within all these types of interaction. In addition, the experts also noted that natural events with high potential of spatially overlapping consequences, for instance, events damaging the national main electricity grid, could be viewed as a multiple hazard.

For each natural hazard, the natural hazard interaction framework in [Figure 2](#) displays if there was any evidence to suggest any types of interaction with other natural hazards. There was evidence to suggest in total 77 interactions, regardless of their type, between a primary and a secondary hazard. Almost all natural hazards examined were indicated to have at least one interaction as both a primary and secondary hazard. However, the evidence does not suggest any interactions with low pressure and cold spell as secondary events.

Based on the interaction type, there was evidence for 56 disposition alteration, followed by 39 cascading, 17 coincident triggering, and 3 additional hazard potential. This suggests that all types of hazard interactions examined are potentially present in a Swedish context but most commonly through a primary hazard changing the environmental conditions so to influence the frequency or magnitude of a secondary event or through a primary hazard directly triggering a secondary one. In the expert workshops, multiple events were often discussed in terms of disposition alteration, using terms like "affecting the propensity for" and in relation to wildfires "When we get these periods of drought, we get a significantly higher (wildfire) risk level than normal".

As a primary hazard, we found evidence for 11 possible interactions with heat wave, the highest of the 20 natural hazards covered. The most common interaction type with a primary heat wave is disposition alteration (9), followed by coincident triggering (4) and cascading (2). At the workshop, the experts considered the combination of long-term drought and heat wave as a frequent multiple hazard in the current climate. In addition, the experts suggested that this combination acts as a precondition if followed by a thunderstorm, which in turn, could directly trigger a wildfire. An example of this type of multiple hazard is the wildfire in Kårböle in 2018. Here, a thunderstorm triggered a wildfire during the prolonged and severe summer drought.⁶² The fire burnt for several weeks with periods of strong winds aggravating the fire.⁶² As the number of days with drought is projected to increase, there will be a longer time span for potential thunderstorm-ignited wildfires. Without adaptation, the number of larger wildfires is likely to increase. Furthermore, the experts identified that burnt areas act as a precondition for landslides since the vegetation no longer contributes to keeping the soil in place. Moreover, the experts point to the burnt area acting as a precondition both for pest infestations, most notably the eight-toothed spruce bark beetle, and for storm-felled trees.

The evidence also suggests that heavy rain is an important primary hazard, possibly interacting with eight of the natural hazards examined. For heavy rain, the most common interaction type supported by the evidence was cascading (7), followed by disposition alteration (6) and coincident triggering (2). The secondary hazards following a heavy rain are almost exclusively hydrological hazards such as floods and debris flows, with pest infestation as the exception. This is in line with the discussions at the expert workshop, describing heavy rain in interactions with fluvial floods, storms, and heat waves, all of which were considered frequent in the current climatic conditions and with considerable consequences. Heavy rain was identified not only as adding to the hazard potential of fluvial floods during high stream flows but also as a precondition for more erosion, landslides, and debris flows. A combined heavy rain and storm event was viewed as frequent, referring to recent events in Sweden, and adding to the hazard potential both by damaging buildings and making floods more severe. Moreover, the experts also viewed the interaction between heavy rain and low temperature as having considerable consequences, but it was seen as less frequent in the current climate and hard to evaluate.

Wildfire is another important primary hazard, supported by evidence for seven interactions with other natural hazards, all of which were of the disposition alteration type. The experts considered some of the interactions with a primary wildfire to be rare or occurring with a large temporal scale (lightning, heat wave), while some interactions were related to the burnt area after a wildfire, increasing the risk of several hydrological events. As a secondary hazard, experts noted that coincident wildfire and storm are greatly adding to the hazard potential and make the emergency response much more difficult in terms of delimiting the fire and increased risk for injuries.

As secondary hazards, we found evidence that hydrological mass movements, i.e., landslides, debris flows, soil movement, and erosion, could be a consequence of 15 primary hazards, the highest of the 20 natural hazards examined. Of the four hydrological mass movement subtypes, we found evidence of landslides as the consequence of 9 primary hazards, followed by debris flow, soil movement (8, 8, respectively), and erosion (4). For secondary hydrological mass movements, the most common type of interaction indicated was disposition alteration (21), followed by cascading (20) and coincident triggering (10). At the workshop, the experts discussed hydrological mass movements as a secondary hazard after both pluvial and fluvial floods through cascading and disposition alternation and after wildfires through disposition alteration.

The evidence also suggests that flood hazards, i.e., coastal, pluvial, fluvial, and flash, are important secondary hazards, interacting with 11 primary hazards. Of the four flood subtypes, we found evidence of fluvial flood as the consequence of 11 primary hazards, followed by pluvial flood (4) and coastal (2), while there was only evidence to suggest that flash flood could be the consequence of one primary hazard. Like the hydrological mass movements, the most common type of interaction for secondary floods was disposition alteration (16), followed by cascading (8) and coincident triggering (3). At the workshop, the experts provided several examples of floods as a secondary hazard, for instance, floods after debris flows and mass movements through triggering.

Interestingly, there was evidence to suggest that pest infestation could be a consequence of 8 primary events. All interactions with secondary pest infestation concern a primary hazard creating favorable breeding conditions for different pests, through water displacement, temperature increases, or forest damage. This is well in line with how the experts discussed pest infestation. They underscored the many ways more favorable breeding conditions for, particularly, the eight-toothed spruce bark beetle were caused by drought, wildfire, storm, and heat wave. For instance, the combination of forest fire and storm was seen as an additional hazard potential since damaged trees fall more easily and in turn triggers a pest infestation.

Influence of climate change on future multiple natural hazards

This section addresses how climate change is likely to influence a subset of the multiple natural hazard interactions presented in the national natural hazard interaction framework. Overall, the experts agreed that several natural hazards have already become more frequent and are expected to become more frequent as the climate continues to change.

Firstly, combined long-term drought and heat wave, which the experts identified as frequent in the current climate, is expected to become more frequent in the future. Climate change scenarios for Sweden indicate likely increased frequencies for both long-term drought and heat waves. Since Sweden is situated relatively close to the north pole, the magnitude of both observed and projected temperature increase is larger than the global average. Climate scenarios indicate up to 60 more days of drought annually in 2100 than today, with expected decreased soil moisture content in Scania and around the two biggest lakes, Vänern and Vättern. Moreover, observed trends for extreme temperature in Sweden clearly show increased frequency of hot extremes. There are no studies of the historic evolution of heat waves in Sweden, and climate scenarios assume that future temperature extremes will increase in line with the average temperature. However, the Swedish Meteorological and Hydrological Institute⁵⁰ suggests that a 20 years event in the current climate is expected to occur every 3–4 years in 2100. Since both drought and heat waves are expected to increase and are caused by the same atmospheric conditions, the probability for compound events increases. Studies of both the historical and future evolution of heat waves as well as of the co-variation between long-term drought and heat waves are needed to better assess future changes. It is, however, clear that global warming will increase the frequency and intensity of heat waves in Sweden. Furthermore, summer precipitation will be relatively unchanged, while soil moisture is projected to decrease, which would suggest increased likelihood of hot and dry conditions.

Secondly, we found evidence for several interactions involving heavy rain as both a primary and secondary hazard. Also, the experts viewed several multiple events involving heavy rain as frequent in the current climate and with higher expected future frequency. Increased heavy rain is a dynamical response to increased atmospheric temperatures. This together with a general increase in precipitation could increase the likelihood of both pluvial and fluvial floods, although the shortened snow season would decrease the likelihood of fluvial flood, especially in the north. Wind speeds or storms are not projected to change significantly. Increased precipitation would give an increase in related hazards since it is not counteracted by the changed (or rather unchanged) likelihood of the other parameters. For combinations of heavy precipitation and heat waves, it is more difficult to project the change. Even if both are expected to increase, it is not obvious that they will occur at the same time or place because there is no direct connection between them in the governing weather situation.

Thirdly, both the literature review and the experts agreed that hydrological mass movements have already become more frequent and are expected to become even more frequent with continued climate change. One expert from the Swedish Geotechnical Institute concluded, “We have seen that it occurs more and more frequently”. Landslides are expected to become more common in areas previously covered by snow wintertime: “We will have more precipitation wintertime there, in north Sweden, and there we have soils that are highly sensitive for precipitation, so we expect more landslides” (Swedish Geotechnical Institute). A continued shortening of the snow season in combination with more precipitation is projected by climate models.

Both observed and projected winter temperatures are increasing, and a larger share of the annual temperature increase will take place in wintertime. The expected results of this are both shorter periods and decreased coverage of ground frost. The most severe wind events in Sweden generally occur during winter, such as the January storms Gudrun and Per. Without ground frost, there is a higher likeliness of trees falling during storms. Less ground frost, thus, acts as the precondition for more severe storm damage. The knowledge about future wind extremes is scarce and hefted with uncertainties.⁵⁰ Even with unchanged wind extremes, the likeliness of this multiple hazard is likely to increase.

Coastal erosion is also seen as increasing due to climate change. The experts note increased coastal erosion following recent storm events. They also note that knowledge about the long-term impacts of more frequent floods and droughts on landslides is lacking, but those are seen as more likely to be problematic rather than unproblematic: “Now it (coastal erosion) is not catastrophic, but coastal erosion is becoming more and more catastrophic” (Swedish Geotechnical Institute).

DISCUSSION AND CONCLUSION

This paper sets out to present a national natural hazard interaction framework for Swedish conditions, following a similar approach as Gill et al.¹⁴ Combining the classifications of natural hazards in Gill and Malamud¹ and the CRED²³ results in geophysical, atmospheric, hydrological, biophysical, and biological hazards. Natural hazards with low historical frequency, low historical impact on the Swedish society, and no known interactions as a primary hazard were excluded from the national hazard interaction framework, resulting in twelve natural hazards. These were further divided, based on examined government agency documents and the expert workshop, into 20 natural hazards of relevance for Swedish conditions. This is similar to the approach used by both Gill et al.¹⁴ and Tilloy et al.¹¹ who identified 33 and 14 relevant natural hazards, respectively.

Four of the six interaction mechanisms identified by De Angeli et al.¹⁰ were used to distinguish between different types of interactions in the framework: cascading, disposition alteration, additional hazard potential, and coincident triggering. Consequently, the framework was constructed as a 20x20 interaction matrix by detecting evidence of interactions between any two hazards in our set of 20. This is a similar approach to that used by both Gill et al.¹⁴ and Tilloy et al.,¹¹ who, however, used fewer types of interactions, one for triggering and one for probability increasing or changed conditions. To detect interactions, three evidence types were used: a systematic literature review of 151 sources, a scoping review of 22 government agency documents and statistical data to assess frequency and magnitude of natural hazards in Sweden, and an expert workshop. This is similar to the data and methods used by Gill et al.,¹⁴ who also added interviews and field observations as sources of data. The systematic literature review also allowed to incorporate more recent literature on natural hazard interactions since Gill and Malamud’s¹ 2014 study. Although we

use diverse evidence to construct our framework, more sources of data would probably further improve the systematics of the study.

The evidence suggests in total 77 (19%) interactions with any of the twenty hazards of relevance for Swedish conditions as the primary one. This overall pattern of interactions is well in line with what Gill et al.¹⁴ found in their construction of a regional multi-hazard interaction framework in Guatemala finding evidence for 50 (11%) interactions, Zuccaro et al.'s¹⁶ hazard matrix for the Santorini area, where experts indicated support for 36 interactions (13%), and the 49 (25%) cascading and/or compound interactions in Tilloy et al.'s¹¹ study based on a comprehensive literature review. In our study we found evidence of at least one interaction for each of the natural hazards examined as the primary. Likewise, there was evidence of at least one interaction as a secondary hazard for all hazards examined, except for low pressure and cold spell. This is also consistent with findings in the Guatemalan¹⁴ and literature-based¹¹ study. The large number of interactions, supported by the evidence, suggests that multiple hazards, in line with what is expressed in the Sendai framework, should be considered in Sweden. The discussions during the expert workshop are also consistent with a view of multiple hazards as something already relatively frequently occurring and with significant consequences on the Swedish society.

Regarding types of interactions, we found evidence of 56 (73% of the total 77 identified interactions) disposition alteration interactions. This order of magnitude is well in line with the 70% increased probability interactions that Gill et al.¹⁴ found in their Guatemalan study but slightly higher than the 54% that Tilloy et al.¹¹ report. However, the Tilloy et al. figure only relates to the cascading literature and not to the interactions supported by compound studies. Since these interactions indicate a statistical relationship, many of the interactions are likely to involve probability interactions. Cascading interactions were the second most common interaction type in our study, involved in 39 (50%) identified interactions. The percentage is significantly lower than the 90% that Gill et al.¹⁴ found in the Guatemalan study and the 80% that Tilloy et al.¹¹ found in the literature study. As geophysical hazards are much more relevant in the Guatemalan context, for which they found 20 interactions with these hazards as triggers, this can partly explain the difference. Their study also included space hazards, which are also acting as triggers in five interactions. We were only able to identify three additional hazard potential interactions. The reason for the low number in relation to the other types may be the gray area that exists between additional hazard potential and disposition alteration since they have similar definitions in this study. This means that some of the interactions considered as disposition alteration may also be well defined as additional hazard potential.

Of the 20 natural hazards studied, heat wave was the most common primary hazard (11 interactions), interacting through cascading, disposition alteration, and coincident triggering. This is significantly higher than that found by both Gill et al.¹⁴ and Tilloy et al.;¹¹ they only identified heat wave as the primary hazard in two and three interactions, respectively. Since heat waves are considered as deviations from normal temperature levels in this study, it could partly explain the difference. This is because it recognizes several disposition alteration interactions with heat wave as the primary event, for instance, where it may lead to strong winds, heavy rain, and snow. Also, this study includes hazards involving snow, which means that it may capture interactions that the other studies have excluded.

The second most common primary hazard was heavy rain (8 interactions), interacting through disposition alteration, coincident triggering, and cascading. This is the case also in the study by Gill et al.,¹⁴ however with more (13) potential interactions with other natural hazards due to their selection of subtype events. On the other hand, Tilloy et al.¹¹ only identified two interactions with heavy rain as the primary hazard. Also here, the reason for this is partly their selection of subtype events. If the hazards included and the aggregation level used in each study are disregarded, the identified interactions with heavy rain as the primary hazard do correspond.

The secondary hazard with the most interactions was fluvial flood (11 interactions), with potential to be a consequence through disposition alteration, cascading, and coincident triggering. This corresponds well with the findings of Gill et al.¹⁴ and Tilloy et al.,¹¹ although some the identified interactions are due to the natural hazards included. Another group of secondary hazards with a relatively high number of interactions are a group of hydrological mass movements including landslides at 9 interactions and debris flow and soil movement, both at 8 interactions. They interact with other hazards through cascading, disposition alteration, and coincident triggering. The findings of our study correspond with other contemporary

studies^{11,14} but with smaller differences connected to the natural hazards included and their subtype events. Both fluvial floods and the hydrological mass movements discussed above are driven by wet extremes, which according to climate research will become more frequent in the future.

Climate research suggests increased frequency and magnitude of both high-temperature extremes^{26,28} and heavy precipitation^{37,38} in northern Europe. According to the constructed framework, increased heavy precipitation may also lead to increases of for instance fluvial, pluvial, and flash floods, which correspond well with recent findings of climate research, suggesting increases in compound flooding.²⁷ Furthermore, the projected increase of heat waves and hot extremes might, according to the framework, lead to more droughts, which may lead to subsequent wildfires due to more and longer periods of fire weather.⁴⁵ The increase of heat waves will also, through disposition alteration, increase the likelihood of hydrological mass movements due to evaporation of the soil. The projected increase of heavy rain makes these hazards even more likely.

The main contribution of this paper is a framework to map out possible natural multi-hazards based on given climate projections of a specific natural event, which can be used for both scientific and practical purposes. As can be seen above, the constructed framework can be used to create possible scenarios of natural multi-hazards by using knowledge on the interactions between natural events given the climate projection connected to one specific hazard. To our knowledge, there are currently no compilations of natural hazard interactions available for the Swedish context, despite the calls from the IPCC¹⁹ and the Sendai Framework⁴ to adopt multi-hazard approaches. Hence, this paper can help practitioners and policy makers of, for instance, emergency management and spatial planning, to adopt a more multi-hazard-oriented approach in their mitigation and preparedness efforts.

Limitations of the study

This study has four major limitations. Firstly, the study excluded natural hazards that were considered of low relevance for Swedish conditions based on low historical frequency, low historical impact on Swedish society, and no known interactions as a primary hazard. Secondly, since the focus of the paper was on interaction types, where there was some kind of relationship, parallel interactions were excluded. Moreover, cyclic triggering hazards were considered rare and only applicable to a small set of natural hazards. Third, the main part of the literature review was conducted during May–September 2020, however, with some needed supplementations at later stages until November 2022. Since evidence from both research and government agencies is likely to amass, it is important to update the framework. For instance, recent studies have demonstrated how natural hazards, such as earthquakes, could interact with the COVID pandemic.⁶³ This should be considered in a future update of the presented matrix. Fourthly, experts were primarily invited from national government agencies with mandate covering the atmospheric, hydrological, and biophysical natural hazard categories. Hence, there was no expert from an agency with a mandate covering biological hazards. This might result in fewer interactions between biological hazards as a primary and secondary hazard, and, consequently, future studies should target such experts.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
 - Lead contact
 - Materials availability
 - Data and code availability
- METHODS DETAILS
 - Three evidence types were used to create the framework
 - Systematic literature review on interactions between natural hazards
 - Review of agency documentation
 - Expert workshop

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.isci.2023.106501>.

ACKNOWLEDGMENTS

The authors would like to thank the editor and the two anonymous reviewers as well as the experts involved for sharing their views and experiences concerning multiple natural hazards. The financial support for the project behind this study, Efficient management of multiple natural events (EMMUNE), from the Swedish Civil Contingencies Agency and Formas, a Swedish research council for sustainable development (grant 2019-06052), is greatly appreciated.

AUTHOR CONTRIBUTIONS

Conceptualization: V.S.G. and M.H.; Methodology: V.S.G. and M.H.; Data collection: V.S.G. (literature, documents, and workshop), M.H. (documents and workshop), and G.S. (climate change); Writing – original draft: V.S.G., M.H., and G.S.; Writing – review and editing: V.S.G. and M.H.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: December 13, 2022

Revised: March 10, 2023

Accepted: March 23, 2023

Published: March 27, 2023

REFERENCES

- Gill, J.C., and Malamud, B.D. (2014). Reviewing and visualizing the interactions of natural hazards. *Rev. Geophys.* 52, 680–722. <https://doi.org/10.1002/2013RG000445>.
- Leonard, M., Westra, S., Phatak, A., Lambert, M., van den Hurk, B., McInnes, K., Risbey, J., Schuster, S., Jakob, D., and Stafford-Smith, M. (2014). A compound event framework for understanding extreme impacts. *WIREs Climate Change* 5, 113–128. <https://doi.org/10.1002/wcc.252>.
- Zscheischler, J., Westra, S., Van Den Hurk, B.J.J.M., Seneviratne, S.I., Ward, P.J., Pitman, A., Aghakouchak, A., Bresch, D.N., Leonard, M., Wahl, T., and Zhang, X. (2018). Future climate risk from compound events. *Nat. Clim. Chang.* 8, 469–477. <https://doi.org/10.1038/s41558-018-0156-3>.
- United Nations (2015). *Sendai Framework for Disaster Risk Reduction 2015–2030* (United Nations).
- Ward, P.J., Daniell, J., Duncan, M., Dunne, A., Hananel, C., Hochrainer-Stigler, S., Tijssen, A., Torresan, S., Ciurean, R., Gill, J.C., et al. (2022). Invited perspectives: a research agenda towards disaster risk management pathways in multi-(hazard)-risk assessment. *Nat. Nat. Hazards Earth Syst. Sci.* 22, 1487–1497. <https://doi.org/10.5194/nhess-22-1487-2022>.
- Ruiter, M.C., Couasnon, A., Homberg, M.J.C., Daniell, J.E., Gill, J.C., and Ward, P.J. (2020). Why we can no longer ignore consecutive disasters. *Earth's Future* 8, 1–19. <https://doi.org/10.1029/2019EF001425>.
- Catto, J.L., and Dowdy, A. (2021). Understanding compound hazards from a weather system perspective. *Weather Clim. Extrem.* 32, 1–18. <https://doi.org/10.1016/j.wace.2021.100313>.
- Gallina, V., Torresan, S., Critto, A., Sperotto, A., Glade, T., and Marcomini, A. (2016). A review of multi-risk methodologies for natural hazards: consequences and challenges for a climate change impact assessment. *J. Environ. Manage.* 168, 123–132. <https://doi.org/10.1016/j.jenvman.2015.11.011>.
- Simpson, N.P., Mach, K.J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R.J., Muccione, V., Mackey, B., et al. (2021). A framework for complex climate change risk assessment. *One Earth* 4, 489–501. <https://doi.org/10.1016/j.oneear.2021.03.005>.
- De Angeli, S., Malamud, B.D., Rossi, L., Taylor, F.E., Trasforini, E., and Rudari, R. (2022). A multi-hazard framework for spatial-temporal impact analysis. *Int. J. Int. J. Disaster Risk Reduct.* 73, 102829.
- Tilloy, A., Malamud, B.D., Winter, H., and Joly-Laugel, A. (2019). A review of quantification methodologies for multi-hazard interrelationships. *Earth Sci. Rev.* 196, 1–20. <https://doi.org/10.1016/j.earscirev.2019.102881>.
- Liu, B., Siu, Y.L., and Mitchell, G. (2016). Hazard interaction analysis for multi-hazard risk assessment: a systematic classification based on hazard-forming environment. *Nat. Nat. Hazards Earth Syst. Sci.* 16, 629–642. <https://doi.org/10.5194/nhess-16-629-2016>.
- Tarvainen, T., Jarva, J., and Greiving, S. (2006). Spatial pattern of hazards and hazard interactions in Europe. In *Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions*, P. Schmidt-Thomé, ed. (Geological Survey of Finland), pp. 83–91.
- Gill, J.C., Malamud, B.D., Barillas, E.M., and Guerra Noriega, A. (2020). Construction of regional multi-hazard interaction frameworks, with an application to Guatemala. *Nat. Hazards Earth Syst. Sci.* 20, 149–180. <https://doi.org/10.5194/nhess-20-149-2020>.
- Kappes, M.S., Keiler, M., and Glade, T. (2010). From Single- to Multi-Hazard Risk Analyses: a concept addressing emerging challenges. In *Proceedings of the Mountain Risks International Conference*, J.-P. Malet, T. Glade, and N. Casaghi, eds., pp. 351–356.
- Zuccaro, G., De Gregorio, D., and Leone, M.F. (2018). Theoretical model for cascading effects analyses. *Int. J. Int. J. Disaster Risk Reduct.* 30, 199–215. <https://doi.org/10.1016/j.ijdrr.2018.04.019>.
- De Angeli, S., Malamud, B.D., Rossi, L., Taylor, F.E., Trasforini, E., and Rudari, R. (2022). A multi-hazard framework for spatial-temporal impact analysis. *Int. J. Disaster Risk Reduct.* 73, 1–25. <https://doi.org/10.1016/j.ijdrr.2022.102829>.
- Oates, C.J., and Alevizou, P.J. (2018). *Conducting Focus Groups - for Business and Management Students 1st Ed* (SAGE Publications).
- Lal, P.N., Mitchell, T., Aldunce, P., Auld, H., Mechler, R., Miyan, A., Romano, L.E., and Zakaria, S. (2012). National systems for managing the risks from climate extremes and disasters. In *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*, C. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, and S.K. Allen, et al., eds. (Cambridge University Press), pp. 339–392.
- United Nations Office for Disaster Risk Reduction (2023). *Terminology - Hazards*. <https://www.undrr.org/terminology/hazard>.

21. Johansson, M. (2018). *Naturolyckor, datakällor och lärande - 10 års erfarenhet av att samla in data till MSB:s naturolycksdatabas* (Centrum för klimat och säkerhet, Karlstad University).
22. Nadim, F., Pedersen, S.A.S., Schmidt-Thomé, P., Sigmundsson, F., and Engdahl, M. (2008). Natural hazards in Nordic countries. *Episodes* 31, 176–184. <https://doi.org/10.18814/epiugs/2008/v31i1/024>.
23. Centre for Research on the Epidemiology of Disasters (2022). General Classification. <https://www.emdat.be/classification>.
24. Myndigheten för Samhällsskydd och Beredskap (2019). Varför Inträffar Skred Och Ras?. <https://www.msb.se/sv/amnesomraden/skydd-mot-olyckor-och-farlaga-amnen/naturolyckor-och-klimat/skred-ras-och-erosion/varfor-intraffar-skred-och-ras/>.
25. Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R.M., van den Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M.D., et al. (2020). A typology of compound weather and climate events. *Nat. Rev. Earth Environ.* 1, 333–347. <https://doi.org/10.1038/s43017-020-0060-z>.
26. IPCC (2021). Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change (IPCC). *Climate Change 2021: The Physical Science Basis*.
27. Ranasinghe, R., Ruane, A.C., Vautard, R., Arnell, N., Coppola, E., Cruz, F.A., Dessai, S., Islam, A.S., Rahimi, M., Carrascal, D.R., et al. (2021). IPCC AR6 WGI Chapter 12: Climate change information for regional impact and for risk assessment (IPCC).
28. Seneviratne, S.I., Abid, M.A., Pinto, I., and Sylla, M.B. (2021). IPCC AR6 WGI Chapter11: Weather and climate extreme events in a changing climate (IPCC).
29. Meier, H.E.M., Kniesbusch, M., Dieterich, C., Gröger, M., Zorita, E., Elmgren, R., Myrberg, K., Ahola, M.P., Bartosova, A., Bonsdorff, E., et al. (2022). Climate change in the Baltic Sea region: a summary. *Earth Syst. Earth Syst. Dyn.* 13, 457–593. <https://doi.org/10.5194/esd-13-457-2022>.
30. Wilcke, R.A.I., Kjellström, E., Lin, C., Matei, D., Moberg, A., and Tyrlis, E. (2020). The extremely warm summer of 2018 in Sweden - set in a historical context. *Earth Syst. Earth Syst. Dyn.* 11, 1107–1121. <https://doi.org/10.5194/esd-11-1107-2020>.
31. Lin, C., Kjellström, E., Wilcke, R.A.I., and Chen, D. (2022). Present and future European heat wave magnitudes: climatologies, trends, and their associated uncertainties in GCM-RCM model chains. *Earth Syst. Earth Syst. Dyn.* 13, 1197–1214. <https://doi.org/10.5194/esd-13-1197-2022>.
32. Zscheischler, J., and Seneviratne, S.I. (2017). Dependence of drivers affects risks associated with compound events. *Sci. Adv.* 3, 1–10. <https://doi.org/10.1126/sciadv.1700263>.
33. Manning, C., Widmann, M., Bevacqua, E., Van Loon, A.F., Maraun, D., and Vrac, M. (2019). Increased probability of compound long-duration dry and hot events in Europe during summer (1950–2013). *Environ. Res. Lett.* 14, 094006–094016. <https://doi.org/10.1088/1748-9326/ab23bf>.
34. Trenberth, K.E., Dai, A., Rasmussen, R.M., and Parsons, D.B. (2003). The changing character of precipitation. *Bull. Am. Meteorol. Soc.* 84, 1205–1218. <https://doi.org/10.1175/BAMS-84-9-1205>.
35. Christensen, O.B., Kjellström, E., Dieterich, C., Gröger, M., and Meier, H.E.M. (2022). Atmospheric regional climate projections for the Baltic Sea region until 2100. *Earth Syst. Earth Syst. Dyn.* 13, 133–157. <https://doi.org/10.5194/esd-13-133-2022>.
36. Rutgeresson, A., Kjellström, E., Haapala, J., Stendel, M., Danilovich, I., Drews, M., Jylhä, K., Kujala, P., Larsén, X.G., Halsnæs, K., et al. (2022). Natural hazards and extreme events in the Baltic Sea region. *Earth Syst. Earth Syst. Dyn.* 13, 251–301. <https://doi.org/10.5194/esd-13-251-2022>.
37. Olsson, J., Södling, J., Berg, P., Wern, L., and Eronn, A. (2019). Short-duration rainfall extremes in Sweden: a regional analysis. *Nord. Hydrol* 50, 945–960. <https://doi.org/10.2166/nh.2019.073>.
38. Christensen, O.B., and Kjellström, E. (2022). Filling the matrix: an ANOVA-based method to emulate regional climate model simulations for equally-weighted properties of ensembles of opportunity. *Clim. Dyn.* 58, 2371–2385. <https://doi.org/10.1007/s00382-021-06010-5>.
39. Donnelly, C., Greuell, W., Andersson, J., Gerten, D., Pisacane, G., Roudier, P., and Ludwig, F. (2017). Impacts of climate change on European hydrology at 1.5, 2 and 3 degrees mean global warming above preindustrial level. *Clim. Change* 143, 13–26. <https://doi.org/10.1007/s10584-017-1971-7>.
40. Teutschbein, C., Grabs, T., Karlsen, R.H., Laudon, H., and Bishop, K. (2015). Hydrological response to changing climate conditions: spatial streamflow variability in the boreal region. *Water Resour. Res.* 51, 9425–9446. <https://doi.org/10.1002/2015WR017337>.
41. Arheimer, B., and Lindström, G. (2015). Climate impact on floods: changes in high flows in Sweden in the past and the future (1911–2100). *Hydrol. Earth Syst. Sci.* 19, 771–784. <https://doi.org/10.5194/hess-19-771-2015>.
42. Gutiérrez, J.M., Jones, R.G., Narisma, G.T., Alves, L.M., Amjad, M., Gorodetskaya, I.V., Grose, M., Klutse, N.A.B., Krakovska, S., Li, J., et al. (2021). IPCC AR6 WGI atlas (IPCC).
43. Coppola, E., Nogherotto, R., Ciarlo, J.M., Giorgi, F., Meijgaard, E., Kadyrov, N., Iles, C., Corre, L., Sandstad, M., Somot, S., et al. (2021). Assessment of the European climate projections as simulated by the large EURO-CORDEX regional and global climate model ensemble. *JGR. Atmospheres* 126, 1–20. <https://doi.org/10.1029/2019JD032356>.
44. Spinoni, J., Vogt, J.V., Naumann, G., Barbosa, P., and Dosio, A. (2018). Will drought events become more frequent and severe in Europe? *Int. J. Climatol.* 38, 1718–1736. <https://doi.org/10.1002/joc.5291>.
45. Kriken, F., Lehner, F., Hausteine, K., Drobyshev, I., and van Oldenborgh, G.J. (2021). Attribution of the role of climate change in the forest fires in Sweden 2018. *Nat. Hazards Earth Syst. Sci.* 21, 2169–2179. <https://doi.org/10.5194/nhess-21-2169-2021>.
46. Berg, P., Bosshard, T., and Yang, W. (2017). Metodutveckling och analyser av klimatscenarier enligt FWI-modellen för framtida brandrisk i vegetation (Sveriges Meteorologiska och Hydrologiska Institut).
47. European Environment Agency. (2017). Climate change, impacts and vulnerability in Europe 2016, H.-M. Fussel, ed. (European Environmental Agency). <https://doi.org/10.2800/534806>.
48. Kjellström, E., Nikulin, G., Strandberg, G., Bøssing Christensen, O., Jacob, D., Keuler, K., Lenderink, G., Van Meijgaard, E., Schär, C., Somot, S., et al. (2018). European climate change at global mean temperature increases of 1.5 and 2°C above pre-industrial conditions as simulated by the EURO-CORDEX regional climate models. *Earth Syst. Dyn.* 9, 459–478. <https://doi.org/10.5194/esd-9-459-2018>.
49. Zhang, W., Schneider, R., Harff, J., Hünicke, B., and Fröhle, P. (2017). Modelling of medium-term (decadal) coastal foredune morphodynamics - historical hindcast and future scenarios of the swina gate barrier coast (southern Baltic Sea). In *Coastline Changes of the Baltic Sea from South to East*, J. Harff, K. Furmańczyk, and H. von Storch, eds. (Springer).
50. Sveriges Meteorologiska och Hydrologiska Institut (2019). Climate extremes for Sweden R. Döschner (Sveriges Meteorologiska och Hydrologiska Institut). https://doi.org/10.17200/Climate_Extremes_Sweden.
51. Sveriges Geotekniska Institut (2015). Inträffade Skred, Ras Och Övriga Jordrörelser. <http://gis.swedgeo.se/rasskrederosion/#>.
52. Wern, L., and Bärring, L. (2009). Sveriges vindklimat 1901–2008 Analys av förändring i geostrofisk vind. *Meteorol. Nr 138/2009 SMHI*.
53. Olsson, J., Berg, P., Eronn, A., Simonsson, L., Södling, J., Wern, L., and Yang, W. (2017). Historiska variationer av extrem nederbörd. *Klimatologi* 47.
54. Isaksson, L., and Wern, L. (2010). Åska i sverige 2002–2009 (sveriges meteorologiska och hydrologiska institut).
55. Sveriges Meteorologiska och Hydrologiska Institut (2021). Temperatur. <https://www.smhi.se/kunskapsbanken/meteorologi/temperatur-1.3843>.
56. Myndigheten för Samhällsskydd och Beredskap (2012). Översvämmningar i Sverige 1901–2010 C. Alfredsson, ed.

57. Sveriges Meteorologiska och Hydrologiska Institut (2021). Historiska torrperioder. <https://www.smhi.se/kunskapsbanken/hydrologi/historiska-torrperioder-1.151112>.
58. Naturvårdsverket (2014). Att utreda relevansen och behovet av lavinprognoser för de svenska fjällarna (Naturvårdsverket).
59. Granström, A. (2020). Brandsommaren 2018-Vad hände, och varför? (Myndigheten för samhällsskydd och beredskap).
60. Sjöström, J., and Granström, A. (2020). Skogsbränder och gräsbränder i Sverige - trender och mönster under senare decennier (Myndigheten för samhällsskydd och beredskap).
61. Wulff, S., and Roberge, C. (2020). Nationell riktad skogsskadeinventering (NRS) - inventering av granbarkborreangrepp i götaland och svealand 2020 (department of forest resource management, Swedish university of agricultural sciences).
62. Skogsstyrelsen (2021). Skogsbruksåtgärder och skador på samhällsfunktioner - analys av situationen idag och i ett framtida klimat samt åtgärdsförslag A. Lomander, ed. (Skogsstyrelsen).
63. Quigley, M.C., Attanayake, J., King, A., and Prideaux, F. (2020). A multi-hazards earth science perspective on the COVID-19 pandemic: the potential for concurrent and cascading crises. *Environ. Syst. Environ. Syst. Decis.* 40, 199–215. <https://doi.org/10.1007/s10669-020-09772-1>.
64. Sveriges Meteorologiska och Hydrologiska Institut (2022). Skalar För Vindhastighet. <https://www.smhi.se/kunskapsbanken/meteorologi/vind/skalor-for-vindhastighet-1.252>.
65. Integrated Research on Disaster Risk (2014). Perils Classification and Hazards Glossary.
66. Sveriges Meteorologiska och Hydrologiska Institut (2021). Nederbördsintensitet. <https://www.smhi.se/kunskapsbanken/meteorologi/nederbord/nederbordsintensitet-1.19163>.
67. The National Severe Storms Laboratory (2022). Lightning Basics. <https://www.nssl.noaa.gov/education/svrwx101/lightning/>.
68. Sveriges Meteorologiska och Hydrologiska Institut (2022). Allmänt Om Torka. <https://www.smhi.se/kunskapsbanken/hydrologi/torka-1.111075>.
69. WSL Institute for Snow and Avalanche Research (2022). Avalanche Types. <https://www.slf.ch/en/avalanches/avalanche-science-and-prevention/avalanche-types.html>.
70. Skogssverige (2021). När Skogen Brinner. <https://www.skogssverige.se/skog/fakta-om/skogsbrand>.
71. Myndigheten för Samhällsskydd och Beredskap (2022). Gräs- och skogsbrand. <https://www.krisinformation.se/detta-kan-handa/gras-och-skogsbrand>.
72. University of California Agriculture & Natural Resources (2022). Glossary. <http://ipm.ucanr.edu/PMG/glossary.html#l>.
73. University of California Agriculture & Natural Resources (2022). Home, Garden, Turf, and Landscape Pests. <http://ipm.ucanr.edu/PMG/menu.homegarden.html>.
74. Grant, M.J., and Booth, A. (2009). A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Info. Libr. J.* 26, 91–108. <https://doi.org/10.1111/j.1471-1842.2009.00848.x>.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Studies' primary and secondary hazards and interaction types	Contained in the Supplementary material	N/A
Documents reporting frequency and magnitude of natural hazards in Sweden	Contained in the Supplementary material	N/A
Software and algorithms		
Mentimeter	Mentimeter AB	N/A
LiU UniSearch (EBSCOhost)	EBSCO	N/A

RESOURCE AVAILABILITY

Lead contact

Further information and requests should be directed to and will be fulfilled by the lead contact, Viktor Sköld Gustafsson (viktor.skold.gustafsson@liu.se).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- This paper analyses existing, publicly available data. The data sources can be shared by the [lead contact](#) upon request.
- Expert workshop data will be shared by the [lead contact](#) upon request.
- This paper does not report original code.
- Any additional information required to reanalyse the data reported in this paper is available from the [lead contact](#) upon request.

METHODS DETAILS

Following a similar approach as in previous studies into natural hazard interaction frameworks,^{10,14} we used a multiple-evidence approach to map interactions between natural hazards and their potential and relevance in our study setting, Sweden.

Three evidence types were used to create the framework

1. A systematic literature review⁷⁴ on interactions between natural hazards and in which way these are described to interact. We see two reasons for conducting the literature review to build up the general natural hazard interaction matrix. Firstly, to review more recent literature since the study by Gill and Malamud (2014). Secondly, since also the research on types of interactions has progresses, we were interested to collate this through systematically reviewing what types of interactions were described in the reviewed literature.
2. A scoping review⁷⁴ of grey literature in the form of Swedish government agency documents and statistical data to collate the frequency and magnitude of natural hazards and events.
3. Engagement with experts and stakeholders via a workshop.

As argued by,¹⁴ these three evidence types make our approach more comprehensive, systematic, and evidenced. This, by exploring potential interactions between natural hazard pairs, based on documented evidence on each interaction's existence. The following sections present these three steps in more detail.

Systematic literature review on interactions between natural hazards

A comprehensive literature retrieval was conducted through the search engine UniSearch supplied by Linköping University (LiU) and driven by EBSCO [©2023/2020-09-31]. It includes databases of scientific articles, books, and reports available for LiU from e.g., Web of Science, Scopus, Science Direct, and PubMed. The Google and Google Scholar search engines were used for broadening the search scope for some specific interactions, where no articles were found through UniSearch.

The literature retrieved mostly includes research articles published in scientific journals. However, it also includes reports and web page documentation from agencies and organizations, and a few media reports. Regardless of their origin, all material included either describes a natural hazard interaction, reports on specific cases where interactions have been identified, or both. Examples on specific case literature included are case studies, observation reports, and hazard impact assessments.

To retrieve articles addressing natural hazard interactions, firstly, each of the 23 natural hazards, including the ones presented in [Table 1](#), was considered as the primary hazard. For each hazard, articles addressing interactions were searched, using search terms as “triggering”, “induced”, and “leading”. For example, with a primary earthquake and secondary landslide, search terms used included “earthquake triggering landslide” and “earthquake-induced landslide”. This led to a few articles describing or studying the interactions of this natural hazard pair. Secondly, the reference lists of the collected literature were searched for additional sources describing the same or similar pairwise interactions. In total, the searches retrieved 151 sources, stored in a literature database, of which 70 are related to [Figure 2](#) and attached as [Table S1](#) to this paper.

Review of agency documentation

Since the study aims to present a natural hazard interaction framework for Swedish conditions, the set of 23 hazards was delimited to those relevant for Sweden. This was accomplished by reviewing Swedish government agency documents and statistical data. Primarily, we searched for compiled statistics over frequency and magnitude for each hazard in Sweden, provided by the Swedish agency mandated to monitoring and reporting about it. In cases where we were unable to retrieve such information, we broadened our search into other sources. However, we ensured the sources were provided or operated by Swedish agencies, institutes, or other state organizations (e.g., universities). We retrieved 23 sources that were used to assess the frequency and magnitude of natural hazards in Sweden, attached as [Table S2](#) to this paper.

Expert workshop

The third evidence type, engagement with experts and stakeholders, also determined multiple natural events relevant for Swedish conditions. We conducted one exploratory workshop with eight experts: two from the Swedish Meteorological and Hydrological Institute, two from the Swedish Geotechnical Institute, two from the Swedish Civil Contingencies Agency, one from Stockholm Environmental Institute, and one from the Centre for Societal Risk Research at Karlstad University. The participant information is presented in below table.

Information about workshop participants and their competencies with regard to natural hazards	
Participants	Competencies
MSB 1	Forecasting and combatting wildfires.
MSB 2	Wildfires, rescue, and response systems.
SGI 1	Mass movements, landslides, erosion and their relation to floods, wildfires, and precipitation.
SGI 2	Landslides, erosion, and management of natural hazards.
SMHI 1	Floods, storms, precipitation, sea levels, and climate change.
SMHI 2	Extreme weather and climate change.
CSR 1	Disasters, learning, and exchange of experiences.
SEI 1	Multiple hydrometeorological events and cumulative and interacting effects.

The workshop lasted for three hours, starting with an introduction to the project and participant presentations. The discussions then started according to the following three topics:

1. Which natural hazards do you see as most relevant for Swedish conditions considering both historical occurrence and the ongoing climate changes?
2. Which combinations of natural hazards do you consider having (i) the highest risk for causing adverse consequences in society and nature in Swedish conditions, and (ii) the highest probability or frequency in Swedish conditions. During this topic, the participants worked in pairs and indicated combinations through the web application Mentimeter. The combinations were then discussed by the full group to allow for more perspectives, experiences, and interaction between the participants.
3. What are the prerequisites to enable forecasts and warnings of multiple natural events?

Three researchers were moderating and observing the workshop. The whole session was recorded with consent from all participants prior to the session, and transcribed verbatim. The natural event combinations identified for the second discussion topic were saved as .pdf files. The analysis of the workshop material was done in three steps. First, the identified combinations of natural events were classified based on their spatial and temporal distribution. For deeper understanding of the onset of each combination, the parts of the transcription where each respective combination was brought up and discussed were read. Lastly, additional information for each combination was collected from Swedish government agency documents to get concrete examples of their occurrence in Sweden. The transcription was also used to identify the state of knowledge multiple natural hazards, the reasoning how they can be understood, and the prerequisites of forecasts and warnings.