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PERSPECTIVE

Disturbance ecology in human societies

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Abstract

1. We define societal disturbances as discrete events that abruptly disrupt the functioning of human societies. There is a variety of such events, including hurricanes, floods, epidemics, nuclear accidents, earthquakes and wars, among others. These disturbances can interact, further increasing their impacts. The severity of disturbances does not only depend on their intrinsic properties (type, intensity and magnitude) but also greatly on human aspects (socioeconomic, historical, political and cultural aspects that define vulnerability).
2. Very large or severe disturbances are infrequent and unpredictable. Yet societal disturbances are intrinsic to human societies; they have occurred through the entire human history and will continue to occur in the future. We can increase preparedness and recovery capacity but cannot avoid disturbances. The type, regime and scale of disturbances change with the development of societies. The increase in population density and complexity also increases the severity of many disturbances.
3. Societal disturbances can temporarily disrupt the functioning of societies. However, when those disturbances are frequent, societies adapt to them and thus disturbances contribute to shape cultural evolution. That is, societal disturbances have a cost at short temporal scales, but they can build up resilience at mid- to long-term scales.
4. Understanding this dynamic view of human systems is becoming more important as climate is changing, humans are overexploiting natural resources and humanity is dense and hyperconnected. We need to take advantage of frequent small disturbances, as they can build resilience and reduce the likelihood of infrequent large and severe disturbances. Our challenge is to encourage actions and policies to be prepared for unknown, unpredictable and unprecedented (infrequent) large-scale societal disturbances that will surely arrive.

KEYWORDS
societal adaptations, societal disruptions, societal disturbances, societal vulnerability

The Mississippi River will always have its own ways;
no engineering skill can persuade it to do otherwise.
Mark Twain

1 | INTRODUCTION

Humanity is embedded in the biosphere, in such a way that people, culture (including economics) and the environment form complex socio-ecological systems—the building blocks of humanity (Carpenter et al., 2009; Folke et al., 2016; Levin et al., 2013). Research on the resilience of these human systems has generally focused on the feedbacks between people (and their health), the economy and environmental changes, including how societies cope with climate change, extreme events and natural disasters (Buma & Schultz, 2020; Chapin et al., 2010; Constanza et al., 1997; Degroot et al., 2021; Folke et al., 2016; Nyström et al., 2019; United Nations, 2015; Xu et al., 2020). Here, we focus on the range of uncontrolled factors that abruptly disrupt the functioning of human societies, such as epidemics and diseases, wars, nuclear accidents, earthquakes, floods and others. We collectively call them disturbances to social systems (or societal disturbances), in an analogy with disturbances to ecosystems (Peters et al., 2011; Pickett & White, 1985). By societal disturbance, we refer to discrete events that abruptly affect the functioning of a society, that is, they temporarily interrupt the normal activities of the affected society. Those normal activities are very diverse and characteristic of each type of society; for instance, in western societies, they may include going to work to get the necessary resources, acquiring food, performing economic/administrative transactions, going to school or visiting the physician. We currently lack a dynamic global view that considers the diversity of disturbances that shape human societies at long time-scales.

Recent research advances on the role of disturbance regimes in shaping ecological systems have greatly increased our understanding of natural systems. Here, we propose that by looking at human societies through the lens of disturbance ecology, we can gain a better picture of the dynamics of our societies (May et al., 2008). To do so, we first describe the concept of disturbance regime applied to societies, and the importance of disturbance interactions. Then, we explain how disturbances have contributed to cultural evolution, despite individually being disruptive events with negative impacts at short time-scales. Overall, we show that disturbances are intrinsic to humanity, and thus, we need to coexist with them in a similar way to how ecosystems have coexisted with natural disturbances through their evolutionary history (Pausas & Keeley, 2009; Pickett & White, 1985; Scott, 2018).

2 | DISTURBANCE REGIME

2.1 | Disturbance types

Like ecosystems, human societies are complex and dynamic systems with flows of matter, energy and information, and they are subject to a range of disturbance types (Table 1). We can characterize the regime of disturbances in human systems by the frequency, severity, spatial extent and seasonality of disturbances (Table 1). The historical origin of these societal disturbances is diverse. Many disturbances are a direct product of human activities (e.g. nuclear accidents and wars), or are indirectly enhanced by humans (e.g. deforestation increases the probability of floods and zoonotic diseases). Yet other disturbances are fully originated beyond human society, such as those related to geological (earthquakes, volcanoes and tsunamis) or meteorological (e.g. ancient megadroughts; Evans et al., 2018, Weiss, 2017) events. One could argue that natural and human-driven disturbances are different, as the former cannot be avoided while the latter can be. However, the distinction between natural and anthropogenic disturbances is often weak for a range of reasons. It is true that the frequency of the so-called natural disturbances may be independent of human activities, but their impact—that is, the degree of societal disruption—greatly depends on socioeconomic and cultural aspects (see below). In addition, some disturbances with a natural origin are magnified in more complex societies. For instance, the impact of the Tohoku earthquake (2011, Japan) was greatly magnified by the

TABLE 1 Examples of disturbances that affect the functioning of human societies and a qualitative indicator of their characteristic regime (frequency, severity, spatial extent and seasonality). Note that some disturbances may be a combination of different types (e.g. floods+epidemics; see Section 3). Severity is not only determined by the intensity of the disturbance but also by socioeconomic factors and cultural legacies from previous disturbances (see Figure 3).

Disturbance type	Examples	Frequency	Severity	Spatial extent	Seasonality
Meteorological	Droughts, hurricanes, floods, ice storms, heatwaves	Mod	Low	Local	High
Biological	Epidemics, pandemics	High	Low-Mod	Local–global	High
Accidental (technological)	Nuclear accidents, urban fires, power blackouts	Low	High	Local	None/Low
Sociopolitical	Wars, terrorist attacks	Low	High	Local–continental	None
Geological	Earthquakes, volcanoes, tsunamis	Low	High	Local	None
Virtual	Stock market crash, internet crash, cyberattacks	Low	Low	Local–global	None
Extraterrestrial	Meteorite impact	Very low	Very high	Local–global	None

fact that it affected the Fukushima nuclear power plant. The onset of agriculture in the Neolithic greatly increased human population density and the concomitant spread and impact of natural diseases and epidemics (Eshed et al., 2010). In addition, some disturbances that seem natural (e.g. landslides, floods and earthquakes) may sometimes depend on human activities (deforestation, fracking, wastewater injection). Furthermore, the idea that human-driven disturbances can be eliminated is naïve; history is stubborn in showing that technological advances do not make humans free of human-driven disturbances, with nuclear accidents and Covid-19 as clear examples. All disturbances can be considered part of the complex and dynamic human system; they are embedded in society, just like the diversity of disturbances to which ecosystems are recurrently subjected (Krüger et al., 2015).

2.2 | Disturbances across time and space

Similar to large ecological disturbances (Turner & Dale, 1998), large societal disturbances are rare events at the individual human time frame; in fact, the larger (or more severe) the disturbance, the rarer it usually is (positive-skewed frequency distributions, with a long tail; Figure 1; Table 2). This negative relation between frequency and intensity or severity makes it hard to predict when a large disturbance

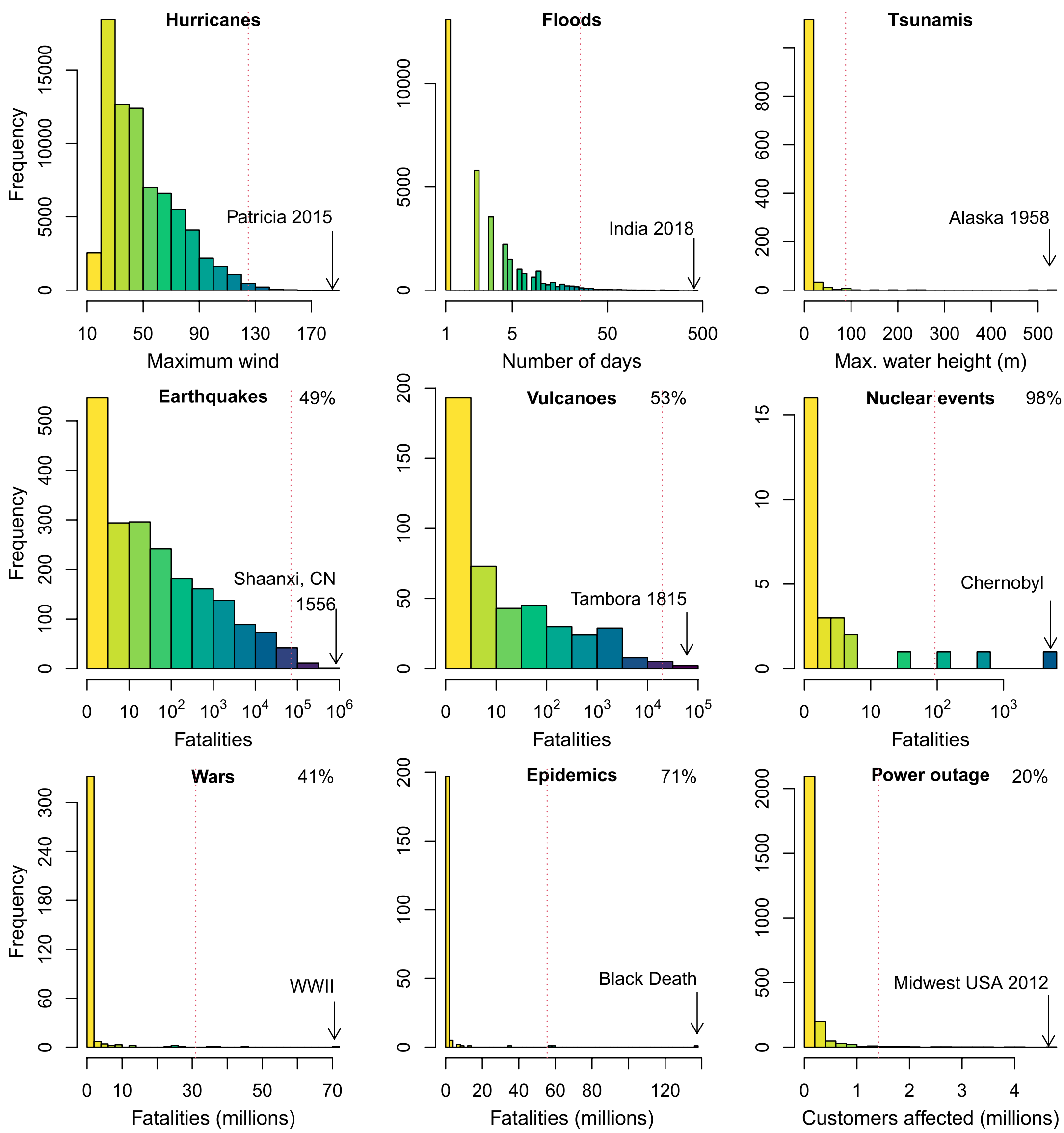

FIGURE 1 Frequency distribution of the intensity or severity of different disturbances. For hurricanes, floods and tsunamis, it refers to intensity (maximum wind speed, duration, maximum water height, respectively); for the others, it refers to severity of the disturbance (fatalities or number of people affected). Note that in some cases, the x-axis is in a log format to improve visualization. For each disturbance, we include the name of the most extreme case and the 99 percentile (vertical line); for the cases related to severity, the proportion of fatalities by the top 1% of the events is also given (value in the top-right). Data refer to global scale except for hurricanes (Atlantic and Pacific Oceans) and power outages (USA). For more details of the data, see Table 2.

TABLE 2 Skewness (values >0 indicate skewness towards large number) and Pearson's kurtosis ('tailedness') of the frequency distribution of different variables related to the severity or intensity (type of variable, S or I) of several disturbances. Unless mentioned in the column 'Period', all data are at global scale. All frequency distributions are positively skewed with long tails.

Disturbance	Type	Variable	Period	*n*	Skewness	Kurtosis	Data[a]
Earthquakes	S	Fatalities[b]	2000 BC to 4/2021	2075	20.37	582.05	4
	I	Magnitude[c]	5/2020 to 4/2021	46,175	0.66	2.12	1
	I	Mercalli Intensity (MMI)[c]	1638 to 1985 (N America)	130,432	0.73	4.63	7
Hurricanes	I	Max. wind speed[b]	1851–2015 (Atlantic & Pacific)	74,904	0.99	3.49	2
Floods	I	Duration (# days)[b]	8/2014 to 4/2021	52,225	15.11	494.86	3
	I	Duration (# days)	1980–2015 (EU)	2211	6.34	69.26	9
	S	Fatalities	1980–2015 (EU)	544	8.35	97.11	9
Tsunamis	I	Max. water height[b]	1610 BC to 4/2021	1180	13.80	240.17	4
	S	Fatalities	426 BC to 4/2021	581	9.83	116.25	4
Volcanoes	S	Fatalities[b]	140 BC to 4/2021	452	9.68	113.52	4
	I	Explosive index (VEI)[c]	1986–2020	1366	0.37	3.12	10
Nuclear accidents	S	Fatalities[b]	5/1946 to 8/2015	216	14.19	205.50	5
	S	Costs[d]	5/1946 to 8/2014	175	9.75	99.95	5
Wars	S	Fatalities[b]	549 BC to 2020	358	7.58	70.70	6
Epidemics	S	Fatalities[b]	400 BC to 2020	2010	9.64	106.60	6
Power outages	S	Persons affected[b]	1/2000 to 2/2021 (USA)	2433	7.36	76.57	8
	I	Duration	1/2002 to 2/2021 (USA)	2023	19.23	533.50	8
Five disturbances[e]	S	Fatalities	2000 BP to 2/2021	3012	24.98	789.73	

[a]Data sources: (1) https://earthquake.usgs.gov; (2) www.kaggle.com/noaa/hurricane-database; (3) www.globalfloodmonitor.org; (4) NGDC (2001); (5) Wheatley et al. (2017); (6) Wikipedia; (7) U.S. Earthquake Intensity Database (1638–1985), NOAA (https://www.ngdc.noaa.gov/hazard/eq-intensity.shtml); (8) https://www.oe.netl.doe.gov/oe417.aspx; (9) EEA, 2016; (10) Smithsonian Institute (https://volcano.si.edu). All accesses in May 2021.

[b]Represented in Figure 1.

[c]Note that these are semiquantitative indices; because of the logarithmic basis of the scale, skewness and kurtosis are much lower than would be using a direct quantitative measure of the disturbance intensity (e.g. energy release, amplitude on a seismogram).

[d]Cost of a nuclear accident is an indirect measure of severity, the higher the cost, the greater the probability of a great disruption (e.g. area affected, infrastructures destroyed, people affected, etc.).

[e]This includes the following disturbances together (and at the global scale): earthquakes, volcanoes, nuclear events, wars and epidemics; tsunamis are not included as the data are not always independent of earthquakes. The data are displayed in Figure 2.

will occur. The most predictable cases are those disturbances with strong seasonality that are expected annually (e.g. hurricanes), although their magnitude, impact and precise location can only be predicted shortly in advance. Many other disturbances are much harder to predict, despite our ability to forecast with some probability that they may occur in a given area. In fact, the zone where a disturbance will occur is often more predictable than its timing. Earthquakes and volcanoes do not occur randomly across the planet but follow the tectonic structure of the Earth's surface; areas under risk of flooding are also easily identifiable. For instance, there is great certainty that there will be a large earthquake in Southern California (San Andreas fault); geologist have even predicted its possible magnitude, but they cannot predict when it will occur (Jones, 2018). The flooding of New Orleans (a city built on a river delta) was widely expected before the Katrina hurricane (2005), but it was not possible to predict sufficiently in advance to evacuate the population (Jones, 2018; Rohland, 2018). There are also cases of unwillingness to trigger evacuation either for strategic reason or for other reasons often related to race, class or gender (Rivera & Miller, 2007). Epidemiologists had long before Covid-19 predicted that a pandemic would spread across the world, given the strong human contact with wildlife (where zoonoses originate) and the huge potential for their spread due to the highly connected structure of 21st century society (Merler & Ajelli, 2010); the uncertainty was (and still is, for future pandemics) where and when it would start. Wars are difficult to predict far in advance despite the existence of some indicators or early warnings (Turchin et al., 2018); in fact, large and severe conflicts are unpredictable—and wars are generally longer and more severe than foreseen.

Despite all the technological advances in forecast modelling of geological, meteorological and epidemiological processes, as well as in early warning systems, there is still a great uncertainty about when and where disturbances will occur. Overall, rare large and severe events occur almost randomly if we regard them at the scale of a human lifetime. Certainly, there are examples of accurate predictions, but before the occurrence of the disturbance, it is hard to

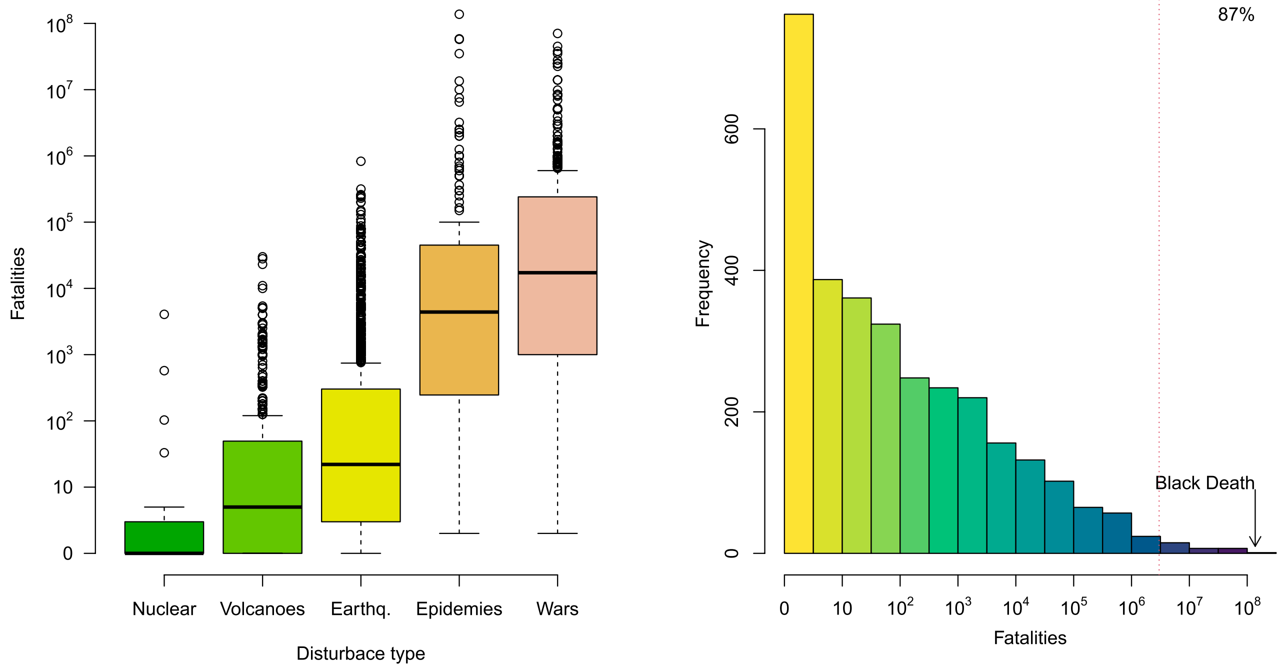

FIGURE 2 Summary of five important disturbances (producing large numbers of fatalities at the global scale; see also Figure 1 and Table 2). Comparison among disturbances (left) and frequency distribution of all five together (right) including the 99% quantile (vertical line). The latter suggests that 1% of these disturbances accounts for 87% of fatalities over the last 4000 years of human history (from 2000 BP to 2020). Note the log scale on both figures, so the frequency distribution (of the raw data) is strongly skewed (skewness = 24.98) with a long tail (Pearson's Kurtosis = 789.73).

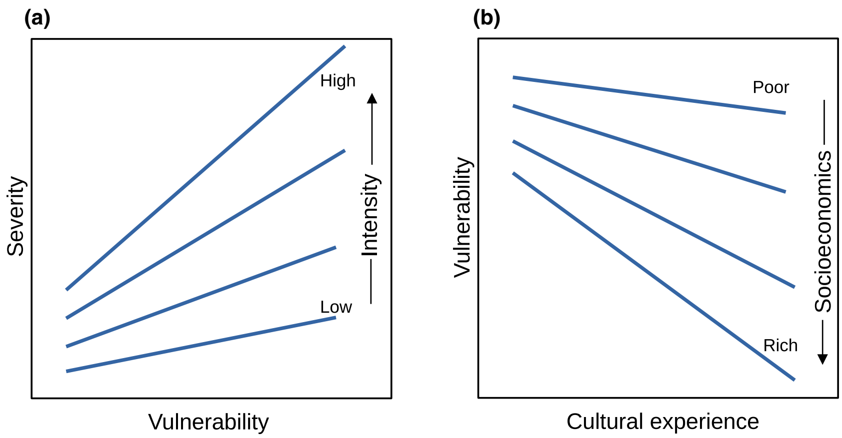

FIGURE 3 Simplified model showing the relationship among the severity of a disturbance, the intensity of the disturbance and the socioeconomic and cultural experience of the population. The severity of a disturbance increases with the intensity of the disturbance (e.g. magnitude of the earthquake, wind speed of a hurricane, infection rate of an epidemic), but also with the societal vulnerability (a). Vulnerability decreases with the socioeconomic level of the population (populations with few resources are more vulnerable) and with their cultural experience from previous disturbances (history, legacies and lessons learned) (b).

distinguish accurate from poor predictions, and thus, they are often neglected (e.g. Davis et al., 2012). Furthermore, large and severe disturbances are not only difficult to predict but they account for most of societal damage; for instance, the most severe 1% of disturbance events—including earthquakes, volcanoes, nuclear accidents, wars and epidemics—has accounted for 87% of the fatalities caused by such events in human history (see the 99th percentile line in Figures 1 and 2), emphasizing the great importance of rare and unpredictable disturbances.

Some part of the temporal and spatial variability of disturbances is due to temporal and spatial differences in the environmental conditions that drive disturbances (i.e. exogenous factors), but also to different socioeconomic levels and cultures (i.e. endogenous factors). Examples of the temporal dimension are the changes in climate that modify the prevalence of diseases, with abrupt consequences. For instance, the cooling of Eurasia during the 6th Century (Late Antique Little Ice Age), which was driven by a series of large volcanic eruptions, has been linked to major societal upheavals, including migrations, diseases (Justinian plague) and major sociopolitical transformations across the Northern Hemisphere (Büntgen et al., 2016). The Black Death also occurred during a cold period (the Little Ice Age). And there is evidence that current global warming may be changing the distribution, frequency and severity of infectious diseases (Wu et al., 2016), large storms (Elsner et al., 2008), flood risk (Reed et al., 2015) and even wars (Hsiang et al., 2013). However, as we will see in the following sections, there are factors intrinsic to human societies that are likely to be more important than temporal and spatial environmental patterns in determining the regime of disturbances, and especially their severity. Such factors include differences in economic levels, histories and cultural heritages, political and power structures, or in technological advances.

2.3 | Disturbance intensity and severity

The intensity of a disturbance indicates its physical strength (e.g. Richter scale of earthquakes, wind speed of hurricanes or infection rate of epidemics), but it does not describe the level of disruption to human societies, and so it is a poor indicator of the magnitude of the societal disturbance. For instance, a category 5 storm caused 23 deaths in Florida (Hurricane Andrew, in 1992) but some 100,000 deaths in Bangladesh (1991 tropical typhoon) (Adger et al., 2005). Even for a given disturbance event, there is a social profile of the victims (e.g. earthquakes as 'classquakes' sensu O'Keefe et al., 1976; pandemic as syndemic sensu Horton, 2020; for heatwaves, see the social autopsy by Klinenberg, 2015), and a recent example is the inability of poorer communities in water-stressed regions to wash, prevent and treat Covid-19 (Levin et al., 2022; Staddon et al., 2020). A given extreme drought differently affects coexisting urban and rural societies, and for rural societies, those based on monocultures may be more vulnerable to extreme weather than those with a diversified agriculture (Lin, 2011). A classic example of social imbalance of victims was the response to the Great Mississippi Flood (1927, the most destructive flood in USA history), in which the evacuation and distribution of supplies among the survivors were focused on White people, while Black survivors were left behind (Rivera & Miller, 2007). Similar discriminatory behaviour was also observed 75 years later when the Katrina hurricane submerged 80% of New Orleans under 6 metres of water (Jones, 2018). In fact, the severity of New Orleans hurricanes largely depends on the expansion of the city in flood-prone areas, mostly occupied by poor people (Kates et al., 2006). The severity of a disturbance therefore partly depends on its intensity, but more importantly on the societal vulnerability (Figure 3a), that is, on the exposure, sensitivity and adaptive capacity of the society, as people are neither equally exposed to disturbances nor equally sensitive to them. Societal inequalities ultimately imply differences in the adaptive capacity to anticipate, resist, cope with and recover from the disturbance (Bankoff, 2017; Chapin et al., 2010; Folke et al., 2016; Krüger et al., 2015). All these factors are strongly related to the socioeconomics and culture of the affected area (Figure 2), which includes historical aspects and power structures.

The number of deaths, in relation to the geographic extent of the disturbance or to the number of persons affected, is a typical indicator for the severity of disturbances in human systems (Figures 1 and 2), but other indicators can be relevant too (e.g. loss of infrastructures, economic costs and poverty increase). Note that we separate severity from spatial extent (Table 1); Covid-19 is probably the most widespread disturbance in human history (e.g. almost everybody has been disrupted by social distancing and lockdowns), but in many places, its severity—in terms of casualties—is lower than other local disturbances such as earthquakes and wars. Considering both the severity and spatial extent (i.e. the overall impact), the medieval Black Death was probably the most disruptive event in human history (an estimate of 75–200 million deaths across Europe, North Africa and the Near East; Figure 2), followed by WWII (some 70 million people killed; Figure 1). It is important to note that different severity indicators may not be correlated, and their use would depend on the question of interest. For instance, there are examples of disturbances of apparently low severity in terms of mortality but of great and long-lasting impact. This is the case of the American Dust Bowl (mid-1930s) in which nobody was directly killed, but two million people were driven off the land; outbreaks of measles, influenza and a fungal lung disease occurred and farmers were forced to change their production systems from grain production to cattle breeding in large regions (McLeman et al., 2014). There are indicators that aim to capture the impact of a disturbance on the quality of life of surviving populations, considering the person's life course (e.g. quality-adjusted life year, disability-adjusted life year; QALY, DALY), and these are being applied to Covid-19 (Briggs & Vassall, 2021). But in some cases, the quantification of long-term costs is not easy; for instance, the burning of the Great Library of the ancient city of Alexandria (48 BC) had an invaluable cultural impact on societies that may still endure today. In short, the physical magnitude of a disturbance is often a poor indicator of its societal impact.

3 | DISTURBANCE INTERACTIONS

Different disturbances may interact in such a way that one disturbance modifies the probability, extent or severity of another disturbance or the capacity to recover (Buma, 2015). The two disturbances may be of independent origin and produce magnified effects (e.g. an earthquake and then a hurricane; compound disturbances) or, more frequently, the first triggers or magnifies the second one (earthquake and subsequent epidemics; linked disturbances). In any of these cases, the actual disturbance to society can only be understood in conjunction, as an emerging phenomenon resulting from the interacting disturbances. In some cases, the interaction is even more complex. For instance, a series of earthquakes hit Haiti (2010) and generated a cholera epidemic; then a hurricane (Tomas) worsened the epidemic and reduced the capacity to recover. There is a plethora of examples of linked disturbances. The most prominent earthquakes in Lisbon and Tokyo (1755, 1923) were severe disturbances not because of the trembling of the ground itself but because of the subsequent fires that spread through the city. A war is a disturbance to society, but sometimes it drives diseases that greatly increase the severity of the war and can even determine its outcome (Snowden, 2019). During the European colonization of America, a large proportion of the mortality was due to diseases that were inadvertently spread from Europeans to native peoples (Wade, 2020). And the independence of Haiti was helped by the yellow fever that devastated Napoleon's army (1803; Snowden, 2019). Many drought and other extreme weather events have also been associated with subsequent plagues (for a review, see Wu et al., 2016) and a variety of other societal effects (Zscheischler et al., 2018). Epidemics also tend to increase after geological disturbances (earthquakes and tsunamis), when access to food, clean water and hygiene is limited, which further increases starvation and social conflicts. In all these cases, we can scarcely differentiate the effect of each component of the disturbance, and thus, we cannot consider them—or evaluate their impacts—as independent events. The effects of these complex interacting disturbances are even more difficult to predict than independent disturbances and may require different approaches (Zscheischler et al., 2018).

More rarely there are also interactions in the opposite direction, that is, a disturbance may reduce the probability, extent or severity of another disturbance. For instance, the Great Fire of London in 1666 destroyed about 80%–90% of homes in the city. However, it is believed to have stopped the Great Plague epidemic by burning down unsanitary houses with their rats and fleas which transmitted the plague; plague epidemics did not recur in London after the fire (Hanson, 2011).

4 | DISTURBANCE AS A DRIVER OF CULTURAL EVOLUTION

4.1 | Lessons learned

By definition, disturbances affect societies negatively (they are disruptive events), at least at short temporal scales. However, many components of society remain unaffected after disturbance (people, infrastructures and organizational systems) and societies gain a valuable experience. These legacies set the basis for recovery and often impose a major impact on the trajectory of society for becoming better prepared for the next disturbances (social memory; Adger et al., 2005). In such way, human societies have continuously learned to deal with disturbances, and thus, disturbances contribute to cultural evolution (i.e. the changes in ideas, behaviours and artefacts that are transmitted between individuals over time; Brewer et al., 2017; Creanza et al., 2017). This learning process reduces societal vulnerability by acquiring resistance (i.e. capacity to be unaffected by a given disturbance) and resilience traits (i.e. capacity to recover functionality after disturbance). Note that resilience in the strict sense (getting back to predisturbance conditions; Pimm, 1984) is not necessarily ideal (and sometimes impossible), as each disturbance provides new lessons for increasing resilience (Olsson et al., 2015). Thus, including adaptation and transformation in the concept of resilience (adaptive resilience) is more appropriate for understanding cultural evolution (Degroot et al., 2021; Diamond, 1997; Folke et al., 2016; Levin et al., 2021; McWethy et al., 2019; Moser et al., 2019; Nyström et al., 2019; United Nations, 2015), and that is how we use it here.

The specific cultural traits acquired for coping with recurrent disturbances (i.e. societal adaptations) are diverse, including changes in infrastructures (e.g. earthquake-proof buildings and early warning systems), social interaction (e.g. cooperation and neighbour networks), health (e.g. antibodies, immunity and vaccination systems), behavioural (e.g. remote working to deter epidemics, mask-wearing) and policies (e.g. institutional preparedness, budget allocated to risk assessment and management and inclusive governance). Such societal adjustments show the adaptive nature of societal resilience, that is, resilience is attained by the capacity to adapt and transform in the face of change (Folke et al., 2016). The most obvious examples are epidemics that enhanced the development of major medical advances and health strategies for resilience (Snowden, 2019), and Covid-19 is just a recent example. However, the examples expand to all types of disturbances. For instance, the Great Fire of Baltimore (1904; one of the most costly disturbances in the US history) stimulated new building codes and the hydrant standardization that greatly enhanced resilience (Grimm et al., 2017). Many regions have acquired flood, hurricane or earthquake cultures in response to the frequency of these disturbances. An emblematic example of this, resulting from the extent and diversity of frequent disturbances (earthquakes, volcanoes, typhoons, tsunamis and floods), is the Philippines, where a culture of disturbances is fully embedded in society (Bankoff, 2017). Another classical example is the adaptation of Japanese society to living in an earthquake hotspot (Clancey, 2006). In short, disturbances provide lessons; they have a cost at a short temporal scales, but they can build up resilience at mid- to long-term scales.

Societal adaptation may require the quick adoption of new and sometimes untested norms (innovation). Social diversity is a major source for innovations (AlShebli et al., 2018; Page, 2008) that enhances adaptive resilience and cultural evolution. The recent acceleration of global environmental changes makes adaptability and transformation key resilience factors. For instance, over many generations, land managers and farmers worldwide have selected appropriate farming methods and crop varieties for dealing with their historic disturbance regime (frequency of droughts, wildfires and pests). However, many of these methods may become anachronistic under conditions of continuous increases in temperature, CO_2, water scarcity and invasive species (i.e. in our current hyperconnected and homogenized world; Nyström et al., 2019). Periods of rapid change can thus be a time of opportunity for innovations and progress framed by experience and social memory (Buma & Schultz, 2020; Endfield, 2012; Olsson et al., 2006). A disturbance may also update anachronistic ideas. For instance, the

Lisbon earthquake in 1755 (the most deadly 'natural' disturbance in Europe) touched the feelings of all Europe in an unprecedented manner (e.g. Voltaire wrote a poem about it) and encouraged societies to take a more scientific view of earthquakes (instead of seeing such events as divine punishment; Shklar, 1990). San Francisco became a modern and progressive city following the 1906 earthquake (Vale & Campanella, 2005). The largest nuclear accident ever, Chernobyl (Figure 1), created a key wildlife sanctuary in Europe, and it has shown us that human presence is more harmful to nature than nuclear accidents (Deryabina et al., 2015). These are just a few emblematic examples that have shaped our culture. In fact, the difficulty in predicting disturbances reflects our inability to predict cultural evolution.

4.2 | Limits to resilience

Although cultural evolution tends to increase resilience, it does not free us from disturbances. Typically, cultural evolution and associated technical advances reduce the frequency or severity of some disturbances (and thus, they may become less predictable), but they also generate novel disturbances (e.g. nuclear accidents), some of them likely to generate systemic risks (virtual disturbances; May et al., 2008). In addition, increased population density increases the severity of many disturbances (Bouwer, 2011). For instance, the next earthquake in southern California, even if the magnitude is the same as the 1906 San Francisco earthquake (Richter magnitude scale = 7.9), is feared to be more disruptive as the region is now more complex and more densely populated. In addition, cultural evolution tends to increase the spatial scale of disturbances. For instance, the spatial scale of a nuclear accident may be much broader than in any previous industrial accident. Enhanced transportation systems also increase the spatial scale of diseases such as the Black Death in the 14th century (Gómez & Verdú, 2017) and Covid-19 in the hyperconnected 21st century. Another clear example of the scalability with technology are wars: huge casualties were rare with old war technologies, but nowadays all it takes is a button, a terrorist or a small error (all quite unpredictable) to wipe out a significant proportion of the world population. The interconnected economies and the large (international) financial institutions may make small financial disruptions less likely, but when disruptions happen, they are huge (e.g. 1930 and 2008 financial crises). Similarly, the globalized food system may have benefit at short time-scales, but infrequent disruptions have broad-scale impacts (e.g. invasion of Ukraine; Boubaker et al., 2022). Our current dependence on the internet makes human societies vulnerable to broad-scale virtual disturbances (what if the Internet crashed for a few days?).

Because not all societies share the same history of disturbances, not all are equally adapted. Thus, the severity of a disturbance may differ across societies, not only depending on the socioeconomic status but also on cultural factors shaped by historic disturbance regimes (Figure 3b). There are many examples of indigenous and rural societies adapted to their disturbance regime (Ford et al., 2020; the Philippine example mentioned above), but also in modern societies (Japanese society has a strong resistance to earthquakes thanks to cultural habits). However, recurrent disturbances enhance resilience and build cultural traits if the recurrence is relatively high (e.g. within a generation). When there is a long interval between disturbances, societal memory is easily eroded. The city of L'Aquila (Italy) has been destroyed twice by earthquakes 300 years apart (1703, 2009; Jones, 2018). Low-frequency or low-severity disturbances are unlikely to build resilience traits. Migrations or relocations may also limit the adaptive capacity because of the loss of local knowledge (e.g. agriculture practices), as has been shown after massive resettlements in Africa (Scott, 1998). Another example is the case of many Americans living in wooden houses in the wildlands. When a wildfire spreads in the Mediterranean environment of coastal California, the severity of the disturbance (in terms of infrastructure lost) is much greater than a similar fire in a traditional Mediterranean (e.g. Spanish) landscape (stone houses concentrated in small towns), despite California's higher economic and technological status. In this case, there is a mismatch between the origin of the culture (North European/British, i.e. non-fire-prone origin) and the environment (Mediterranean fire-prone California). It will require some time to culturally adapt appropriate behaviour. Similarly, the strong political changes through history in New Orleans have been suggested to limit their hurricane culture (Rohland, 2018).

In many societies (especially in high-income societies), there is a tendency towards zero-risk policies to any disturbances, even if they are small or of low severity (the zero-risk bias; Raue & Schneider, 2019). This overprotection often has the unintended consequences of increasing the probability of large and severe disturbances. In many fire-prone ecosystems, excluding all fires leads to a vegetation (fuel) buildup and an increased risk of high intensity wildfires (Covington & Moore, 1994). Similar processes also occur with societal disturbances. Some small stock market fluctuation weeds out vulnerable firms early enough to minimize the probability of strong economic crashes in the long term (Taleb, 2014). Hackers also make the systems stronger to large virtual disturbances. Geologist know that light earthquakes reduce the cumulative energy and prevent severe earthquakes (Jones, 2018). Building a dam to prevent floods based on the historical variability of storms means that if an unprecedentedly intense rainstorm occurs, the dam may not be appropriate, and all cumulative water (and energy) could generate a stronger (catastrophic) flooding. There have been many cases of dam breaching; in fact, to avoid them, dams are sometimes opened (or even dynamited) during extreme storms. The illusion of stability provided by the dams is often associated with the expansion of urban areas in apparently safe zones, which further increases the severity of the future flooding ('levee effect'; White, 1945), as recurrently occurred in New Orleans (Kates et al., 2006). That is, avoidance of small disturbances increases the probability of a larger or more severe ones. We need to take advantage of disturbances, and even allow at least small ones as they may act in a way analogous to vaccines (i.e. for our own benefit); and this is hardly considered in most risk management programmes.

One of the challenges of our civilization is to be able to build resilience to very low-frequency (unknown, unprecedented) disturbances that can be large and severe (Figure 1), and this requires integrating disturbance dynamics and the associated risks as part of our society. That is, we need to reduce our zero-risk bias; public pressures too often strive for zero risk (at a given moment) and may push policymakers away from prioritizing long-term stability; the short-term political cycles only enhance this behaviour.

5 | CONCLUDING REMARKS

Human societies are subject to a wide range of disturbances (Table 1). Rather than being exceptional, disturbances are deeply embedded in societies; they continue to happen despite scientific, technical and cultural advances. With such advances, some disturbances may become less frequent and severe, but others appear, often with effects at a greater spatial scale and greater overall impact. Whereas disturbances may seem rare events (surprises) at the scale of our individual lifespan, they occur repetitively at the scale of societal life span. Their severity does not only depend on intrinsic properties of the disturbance (type, intensity and spatial extent) but also greatly on human aspects (socioeconomic level, inequalities and cultural aspects that define vulnerability). Despite disturbances affecting societies negatively (short-term cost), in most cases societies survive, learn, adapt and in turn modify the disturbance regime; that is, societies and disturbances co-evolve over time. Accepting and integrating disturbances as a part of society, rather than considering them as rare external events, is the first step for building long-term resilience. Aiming for eliminating disturbances would only frustrate society; our aim should be a sustainable coexistence with disturbances. In fact, frequent small disturbances (e.g. small social conflicts, light earthquakes or stock market fluctuations) build resilience and often reduce the likelihood of infrequent large disturbances (e.g. wars, severe earthquakes, economic crashes).

Understanding this dynamic view of human systems, where disturbances are key components for cultural evolution, is becoming more important as climate is changing, humans are overexploiting natural resources, and humanity is dense and hyperconnected. These unprecedented factors are changing our disturbance regime—that is, modifying the probability, distribution, severity and extent of many disturbances. Our challenge as a society is to shape our cultural evolution (building resistance and resilience) by promoting actions, policies and organizations for reducing the frequency and impacts of severe disruptions. This will certainly require increasing the spatial scale of preparedness and responses through transnational and global actions (United Nations, 2015) as the scale of disturbances is increasing too. The path for reaching this challenge may not be straightforward and requires emphasizing the importance of sound scientific-based and multidisciplinary decisions while accepting epistemic limitations, and thus leaving room for trial-and-error (adaptive) learning. We need to take advantage of any disturbance and consider it as an opportunity to learn and build resilience for larger future disturbances; in fact, Covid-19 has most likely prepared us for future pandemics that could be more aggressive. Care must be given to assess power relations related to disturbances and avoid increasing inequalities in post-disturbance societies. Coping with disturbances will be easier if we benefit from diversity, redundancy, flexibility and modular organization in human societies (AlShebli et al., 2018; Chapin et al., 2010; Levin et al., 2021; Page, 2008; as in ecological systems; Loreau et al., 2021). But it is important to be aware that large and severe disturbances may not be predictable by models and experience. That is, we must be prepared not only for known unknowns but also for the unknown unknowns that will surely arrive.

> 'The future can't be predicted, but it can be envisioned and brought lovingly into being. Systems can't be controlled, but they can be designed and redesigned. We can't surge forward with certainty into a world of no surprises, but we can expect surprises and learn from them and even profit from them' (Meadows, 2008).

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Juli Pausas conceived the idea and wrote the manuscript. Alexandro Leverkus contributed to the final version.

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CONFLICT OF INTEREST STATEMENT

The other authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All data used in this research are publicly available in the sources mentioned in Table 2.

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