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Review

The Disaster Risk, Global Change, and Sustainability Nexus

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Abstract: Until the 1970s, disaster risk was perceived as a direct consequence of natural hazards. Gradually, disaster risk has come to be understood as a compound event, which lies at the intersection of hazards, exposure, and vulnerability of the exposed elements. After decades of research and lessons learned from mega-disasters, social scientists have introduced the social dimension of disaster risk, and the prevailing understanding is that disasters are also a human construct. Now, due to climate and global environmental changes, even the natural component of hazards is being altered by anthropogenic activities, changing hazard susceptibility, coverage, frequency, and severity. This review retraces the brief history and evolution of the global understanding of disaster risk as a compound event, in parallel with research on global environmental change. It highlights the main milestones in this area, and shows that there are tight connections between trends of disaster risk and global change. This paper aims to demonstrate the need to better consider the role of global environmental change in disaster risk assessment. In 2015, three major new agreements were reached to improve global environmental governance: the new Sendai Framework (2015–2030), the post-2015 development agenda with the 17 Sustainable Development Goals (SDGs), and the Climate COP21 in Paris. These all include a clear focus on disaster risk reduction; however, several aspects of disaster risk linked with global environmental changes are still not clearly addressed by the main stakeholders (governments, insurers, or agencies). As the complexity of risk unfolds, more actors are getting together; the need for a holistic approach for disaster risk reduction has become clear, and is closely connected with achieving sustainable development.

Keywords: disaster risk reduction; sustainable development; natural hazards; global environmental change; climate change

1. Introduction

1.1. Understanding the Compound Nature of Risk

With the exception of droughts, we tend to see disasters as sudden events. The triggers of disasters, such as earthquakes, tropical cyclones, or landslides, are indeed rapid events. However, in most cases, disaster risk accumulation is slow and continuous over time. Disasters are the cumulative consequences of incremental changes stemming from everyday actions following inappropriate decisions [1]. One analogy is to compare the process of creating disaster risk with building a house of playing cards by stacking cards on top of each other. The house of cards will collapse if you place it on shaky foundations. It will also collapse if any of the necessary supporting elements are removed, or if it is exposed to a disturbance. In fact, its collapse is inevitable! The process of an inflating disaster risk bubble threatening our societies, like a house of cards, is slowly built, but risk can be suddenly released by the shock of a hazardous event.

The perception of disaster risk as a dynamic compound event, largely triggered by anthropogenic actions interlinked with global change, is still a fairly recent concept and not yet well integrated in disaster risk reduction processes. One of the reasons for this may be that understanding risk requires interdisciplinary expertise, including earth sciences, hydrology, climate, environmental sciences, socio-economics, climate change, sustainable development, land planning, governance, and so on. The Disaster Risk Reduction (DRR), Climate Change Adaptation (CCA), and Environmental and Development communities are gaining in mutual understanding. However, this is taking time. It already took decades just for the idea that disaster risk was also a human construct to be accepted. This understanding gradually emerged from scientific theories and lessons learned from mega-disasters since the 1970s. Until then, research conducted on risk was predominantly hazard-orientated [2,3].

The choice of the term "natural disasters" reflects the historical idea that these events were thought to be random, exceptional events, or acts of nature [3].

Pioneering work from Gilbert White [4] introduced the social dimension of disasters as a research field [2,5]. By the end of the 1970s, this change in perspective had evolved into the prevailing definition of risk, which emerged from the United Nations Disaster Relief Organization (UNDRO) group of experts meeting [6,7]. This definition is commonly used either in its original form, or as a basis for the multiple derivatives that followed. The UNDRO [6] defines risk with three components: natural hazards, elements at risk, and vulnerability, where risk is the expected number of losses [6–9]. This recognizes that disaster events result from a series of independent components, including hazard types which vary in frequency, intensity, duration, rapidity of onset; type and number of exposed elements (assets, population, environmental features); and the vulnerability of the exposed elements arising from various physical/structural, social, economic, and environmental factors. Since then, this definition of risk has been adopted in numerous global studies [10–13].

During the 1980s, the concept of vulnerability gained importance, supported by the social science community [14]. The recognition of human vulnerability was a revolutionary change in the understanding and perception of disaster risk; disasters were no longer seen as purely natural, random phenomena (so-called "acts of God"). Publications such as Hewitt [15] contributed to a globalized social theory of natural disasters.

As several disciplines, from engineering to social sciences, were studying risk simultaneously, risk definitions evolved in parallel, creating what Thywissen [16] called a "confused Babel" amongst the different risk communities. No less than six different schools that have elaborated on the concept of vulnerability can be identified [17]. In this present article, these concepts are defined by the definitions provided by the United Nations International Office for Disaster Risk Reduction (UNISDR), aiming towards a standardization of definitions [18] (Box 1).

Box 1. A common understanding of the definitions of risk and its components (sources of definitions: UNISDR, 2009).

The UNISDR terminology aims to promote common understanding and common usage of disaster risk reduction concepts.

Risk: *The combination of the probability of an event and its negative consequences.*

Disaster Risk: *The potential disaster losses, in lives, health status, livelihoods, assets and services, which could occur to a particular community or a society over some specified future time period.*

Hazard: *A dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage.*

Exposure: *People, property, systems, or other elements present in hazard zones that are thereby subject to potential losses.*

Vulnerability: *The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard.*

Coping capacity: *The ability of people, organizations and systems, using available skills and resources, to face and manage adverse conditions, emergencies or disasters.*

Resilience: *The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions.*

1.2. Global Recognition of Risk

Engineers, social scientists, and the insurance sector have traditionally mostly concentrated on disaster risk at a local to national scale. The impetus for a global perspective in risk analysis emerged in the mid-1980s. The Chernobyl nuclear accident (1986) and the discovery of the hole in the ozone layer (and subsequent signing of the Montreal Protocol in 1987) may have contributed to global awareness that environmental impacts do not stop at national borders. It was also during this time that the United Nations General Assembly proclaimed the 1990s to be the International Decade for Natural Disaster Reduction (IDNDR) [19].

Gradually, throughout the 1990s, as a result of developments in the social sciences, the idea that natural disasters are a construct resulting from human behaviors was taking a firm hold. The "un-natural" status of natural disasters was unveiled [2]. Risk was increasingly understood to be dependent on both the hazard and the population's vulnerability. The conclusion from the US Natural Hazard Assessment that "disasters are designed" could no longer be denied [20].

The International Decade for Natural Disaster Reduction came to an end, nonetheless, with several mega-disasters affecting large areas. According to the Emergency Database (EMDAT), in 1998, hurricane Mitch devastated Central American countries, killing 18,820 people. While Mitch was an extreme hurricane, it also set off multiple catastrophic disasters triggered by flash floods and landslides, resulting from decades of unsustainable patterns of land use, territorial occupation, and natural resource mismanagement [21].

The El Niño of 1997/1998 was one of the strongest El Niño events of the 20th century [22]. It disrupted the regional climate, triggering droughts in Indonesia, the Philippines, Bolivia, Southern Africa, Northeast Brazil, and Central America, and heavy rains in parts of Kenya, Peru, and Southern Brazil. It led to losses totaling tens of billions of dollars [22]. Droughts set the conditions for large wildfires which hit Indonesia, Far East Russia, Central America, Canada, and Brazil [23].

It was obvious that more action on disaster risk reduction was needed. In 2000, the UN General Assembly established the United Nations International Strategy for Disaster Reduction (UNISDR), to carry on the work initiated in the 1990s [19].

1.3. Global Environmental and Climate Change Studies

An alternative entry to this field of research followed the emergence of the scientific field of global environmental change in the 1970s, which continued to develop in parallel with the research on disaster risk.

1972 was a pivotal year for environmental awareness. The photo of planet Earth taken by Apollo 17 revealed the finite size of our planet in the middle of the cosmos. The first civil satellite—the *Earth Resources Technology Satellite (ERTS-1)*, later renamed *Landsat*—started monitoring the earth's land cover. The United Nations Conference on the Human Environment was held in Stockholm, and led to the creation of the United Nations Environment Programme (UNEP).

In the mid-1970s, the human consumption of natural resources reached the renewable capacity of the planet [24]. Meadows and others applied a method for understanding the dynamic behavior of complex systems to a simplified Earth system. They fed their model with a variety of different inputs, such as accelerating industrialization, rapid population growth, widespread malnutrition, depletion of non-renewable resources, and a deteriorating environment. Their conclusions were published in *The Limits of Growth* [25], forecasting a global collapse before 2100 if humans failed to achieve sustainability in their development. These conclusions were heavily criticized by economists, some even going as far as stating that the conclusions in the report were "complete nonsense". Yet, there were other economists who supported the need for zero growth. For example, Georgescu-Roegen [26,27] applied Newton's laws of thermodynamics to the economy in order to demonstrate the impossibility of continuous economic growth based on a fixed amount of resources. Other mathematical models were used to criticize the neoclassical growth theory [28]. Nevertheless, calls for reducing the human footprint on the environment [29] were largely ignored. Forty years later, the assessment of unsustainable development has been largely confirmed [30]. Humans are now using more than 150% of renewable resources [24]; as an allegory, we are yearly withdrawing 1.5 times more cash than our annual revenue (renewable natural resources), thus leading to a decline of our capital. We cannot indefinitely catch more fish than the number that hatch each year, and cut down more trees than are grown. We observed a decline of 60% in the population sizes of vertebrates between 1970 and 2014 [31]. This decline is affecting the tropics more seriously, as compared with temperate environments.

The development of global environmental change research further revealed that a cluster of other global concerns (e.g., deforestation, pollution, decline of biodiversity) was threatening the ecosystems that sustain human well-being [32]. In 1987, the Brundtland report introduced the concept of sustainable development supported by the three pillars: social, environment, and economic [33]. In 1990, the Inter-Governmental Panel on Climate Change (IPCC) published their first report (IPCC, 1990), and in 1992, The United Nations Conference on Environment and Development (UNCED) was held in Rio. These events contributed to raising awareness of global environmental issues within governments and amongst the wider public.

1.4. Global Change

Global change can be defined as the sum of the consequences from development. Some consequences have been highly beneficial to humans (health, life expectancy, and comfort), whereas human population growth—especially when associated with increased individual consumption of natural resources and industrialization—has produced significant impacts on the physical and biological environment. Global change encompasses all changes ranging from demography, social, economic, use of energy, and natural resource changes, as well as changes affecting the physical conditions of the Earth system, such as the geosphere-biosphere or climate. These changes have often followed exponential trends since 1950 [34]. The environmental part of global change can be referred as Global Environmental Change, and include the modification of the physico-chemical composition of the atmosphere (leading to climate change and climate variability), soil degradation, ecosystem decline, biodiversity losses, pollution, and global dissemination of invasive species, among others [35].

Turner differentiates two types of global environmental change: systemic and cumulative [32]. Global systemic changes include localized sources of change leading to global effects: for instance, climate change, the hole in the ozone layer, and sea level rise. The second type is global cumulative changes, which include multiple transformations with local impacts, but which are nevertheless global because they are occurring on a worldwide scale. Loss of biodiversity and soil erosion fall into this category. The term "change" was deliberately chosen for its neutral meaning (a change can be either good or bad), but what is usually meant is global environmental degradation [3].

Changes are inherent to planet Earth's system. Without changes, there would be no life. Before anthropogenic influence became so massive, most changes within the planet originated from natural phenomenon such as volcanism, tectonic movements, erosion from rivers and glaciers, and modification of our planet's rotation axe. These changes were slow, allowing for living species on earth to adapt through evolutionary processes [36]. It often takes multiple generations to adapt to new conditions. Ecosystems are not designed for quick adaptation. The meteorite that hit our planet 65.5 million years ago [37,38], led to the fifth massive extinction of biodiversity. It then took 10 to 40 million years to recover to a similar level of biodiversity [39].

Today, more than 50% of the terrestrial planet has been transformed by human activities [40]. To feed the increasing population and produce more meat, large stretches of forests are being cleared and converted into cropland and pastures [41]. Between 2010 and 2015, 11 million ha of forest were cut down, mostly for conversion to crop land [42]. The largest deforestation occurred in Amazonia, Borneo and the Sumatra islands (Indonesia), and in Africa, as well as in the boreal forests of Canada and Russia. More than half of the world's mangroves have been cleared, often for conversion to fish/shrimps farms (see the example from Honduras in Figure 1).

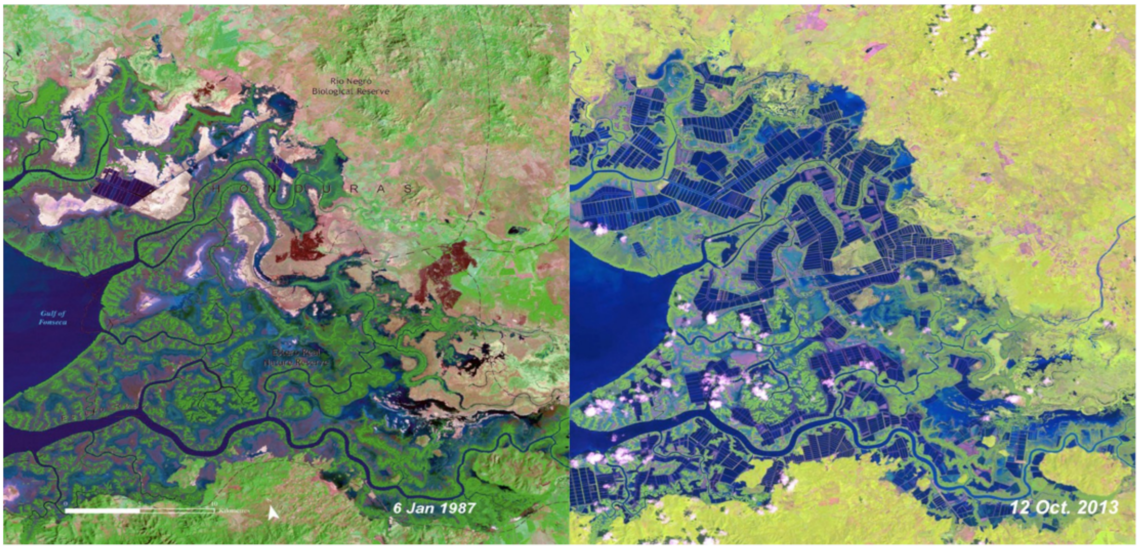

Figure 1. Conversion of mangroves into shrimp farms in Honduras (left extracted from UNEP, 2005; right image analysis by Pascal Peduzzi using Landsat 8 from 2013).

Every year, between 3.5 million km^2 and 4.5 million km^2 of land is burnt, an area comparable to half of Australia [43,44]. Moreover, mines, energy exploitation (e.g., petrol, tar sand, uranium), and metal extraction (such as iron, gold, or copper) are not only transforming landscapes locally, but are also significant sources of pollution for rivers [45–47].

Oceans are under multiple anthropogenic threats, namely acidification, overfishing, oil spills, pollution from chemicals and fertilizers, invasive species, extraction of sands, and pollution from waste. It is estimated that approximately 6.4 million metric tons of waste enters the oceans every year, and that "over 13,000 pieces of plastic litter are floating on every square kilometre of ocean" [48]. Fish stocks fished within biologically sustainable levels have declined from 90% in 1974 to 66.9% in 2015 [49], and 93% of the total ocean area is exploited to the limit or overfished [49].

The use of petrol and other fossil fuels emits Green House Gases (GHG). Their higher concentrations in the atmosphere are responsible for climate change [50].

All of these changes are now occurring at a rate which is too rapid for Earth's species to adapt, and we may be experiencing the sixth massive biodiversity extinction [50] at a rate exceeding about

1000 times the background rate of species losses [51–54]. This ranges from full extinction of species, to example of massive reductions in species numbers (such as seen in the world's tiger population, which has dropped by 70% since 1970 [24]), to an overall decrease in the total insect population. In reference to the latter, they are less iconic, but insects are also called "*the little things that run the world*" given their crucial roles in ecosystems [55]. In contrast to the five previous mass extinctions experienced on earth, the current biodiversity loss is largely of human origin [56].

What are the causes of such rapid change? The main triggers are interconnected: demographic growth (according to the UN population divisions, the world population doubled from 1970 to 2015), increases in individual consumption, and changes in technology (which can lead to both positive and negative impacts) [57]. Additionally, planned obsolescence (Planned obsolescence (or "built-in obsolescence") is decision to design and manufacture products so that they become out of date or useless within a known time period. It aims at multiplying the selling of such products.) [58,59], and so-called "externalities" (the environmental, health, and social costs of something) which are mostly not included in the prices of goods and services, and significant factors. Furthermore, the cost of repair exceeding production costs, low transport costs (allowing the increase in the distance between market and production, thus desynchronizing consumer purchasing power and production costs), and unsustainable use of natural resources, as well as climate change resulting from GHG emissions and deforestation, must be considered.

These changes are both exacerbating disaster risk from natural hazards, and generating new risks for human societies.

2. How is Disaster Risk Linked with Global Change?

Rockström and others [60] have identified nine planetary boundaries, within which it is expected that humanity can operate safely. These boundaries were quantified for climate change; ocean acidification; stratospheric ozone; the biogeochemical nitrogen cycle (which limits industrial and agricultural fixation) and the phosphorus cycle; global freshwater use; land system change; the biological diversity loss rate; chemical pollution; and atmospheric aerosol loading. According to their studies, humanity has already transgressed three of these boundaries, namely climate change, rate of biodiversity loss, and changes to the global nitrogen cycle. Transgressing one or more planetary boundaries can lead to the possibility of crossing thresholds, and triggering non-linear, abrupt environmental change within continental- to planetary-scale systems [60–62].

An increase in exposure induced by population and economic growth has been identified as the main factor inflating disaster risk in the near future [12,13,63]. Climate change can exacerbate hazard frequency and/or intensity [11–13], and also has a magnifying effect. Meanwhile, there is also a growing consensus that ecosystem decline is also increasing disaster risk, either by altering the susceptibility of hazards, or by reducing the action of mitigating impacts [11–13,63].

Climate change and ecosystem decline are increasingly being considered as part of the equation of disaster risk. In this framework, disasters can no longer be considered as being natural, but as consequences of human activities and decisions, and also as part of global environmental change processes [3]. Population growth, economic growth, climate change, and ecosystem decline are all components of global change and disaster risk (see Figure 2). The UNDRO equation [6], mentioned previously, is clearly a simplification. Not only is the actual risk more complex, but with development, climate change, and environmental changes, the risk is also dynamic, requiring regular re-assessment.

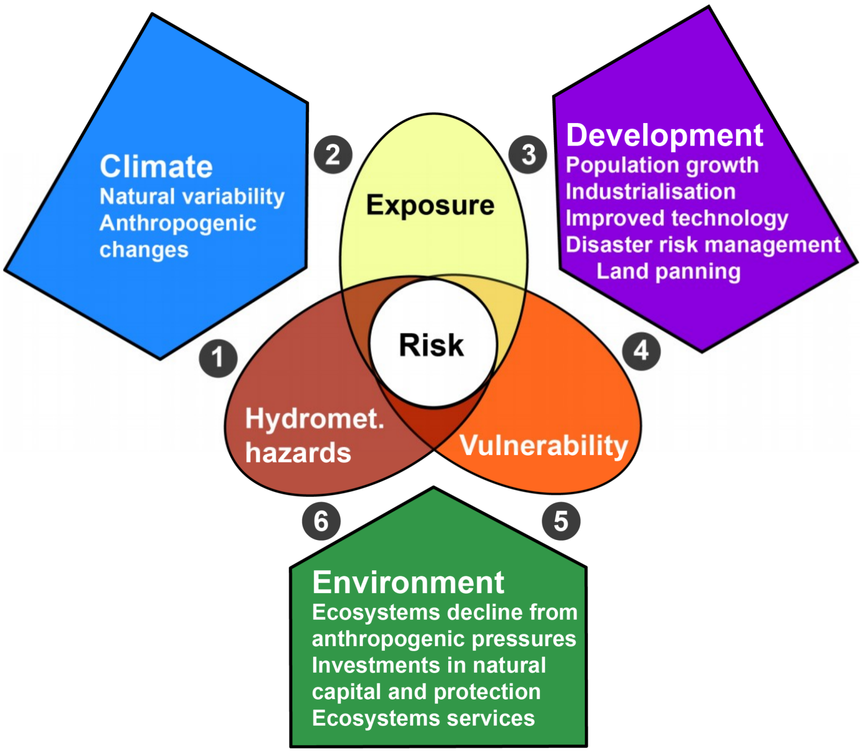

Figure 2. The components of risk, along with exacerbating factors from global change. 1. Climate change increases hazards frequency/intensity. 2. Change in area exposed to hazards. 3. Population and economic growth increase exposure. 4. Vulnerability is reduced by improved in technology (except for Nat-Tech), disaster risk management and land planning. 5. Healthy ecosystems can help improving resilience in post-disaster by providing freshwater, fishing and other natural resources, conversely, ecosystem decline can increase vulnerability. 6. Healthy ecosystems may reduce hazards frequency and intensity. Protective ecosystems services, such as vegetated slopes (reduces landslides), coastal ecosystems (reduces wave energy, vegetation in urban areas against heat islands, and urban floods).

Global Assessments for Understanding Risk and Lessons from Mega-Disasters

While the concept of disasters resulting from incremental actions which lead to risk accumulation [1] was spreading within the disaster risk community, this was not necessarily the prevailing understanding in governments, not to mention among the general public. The main perception (and this belief still persists in many places) was that disasters are random natural phenomenon [3]. This means that most actions, from governments and specialized agencies, have been (and in many cases, still are) focused on disaster response and relief, rather than re-thinking human development and land-use planning [64]. In spite of studies showing a ratio of one dollar invested in prevention being worth multiple dollars in response [65], 96% of funds are still spent in disaster response compared to just 4% for prevention, representing a meager 0.07% of the total global development fund.

Despite all the progress made in disaster risk reduction, out of the top 20 killer disasters (>20,000 killed) and the top 20 economic losses from disasters since 1975, 50% and 75% of these disasters, respectively, occurred in the post-2000 era. These events have triggered new insights into global disaster risk, and new approaches to global risk assessments have emerged.

In the early 2000s, in order to mainstream the idea that disaster risk is an unresolved issue of development, the United Nations Development Programme (UNDP) decided to develop an index to comparatively assess disaster risk between countries, and to identify the underlying factors of risk in a quantitative way [10].

Countries are not equally exposed to natural hazards. Differences in geophysical factors (slopes, elevation, proximity from the shore, or geological faults, inter-tropical location, etc.) are parameters that influence a higher occurrence and severity of hazards [8]. Therefore, extracting vulnerability parameters requires extensive standardization. After four years of research, the Disaster Risk Index (DRI) was published in 2004 in the UNDP report entitled "Reducing Disaster Risk: A Challenge For Development" [10]. The DRI was the first attempt to produce a global, quantitative approach to assessing risk due to multiple hazards (tropical cyclones, drought, earthquakes, and floods). It identified the role of vulnerability parameters such as poverty, underdevelopment, urban growth, and deforestation. However, at the time of this report, several methodological gaps and issues remained regarding droughts. The methodology and the final version of the DRI were finally published in 2009 [66].

The UNDP 2004 report was the first analysis to include exposure to natural hazards with a global focus. It was computed using population distribution models at a 5 × 5 km resolution, and placed emphasis on the identification of vulnerability parameters. The risk was calibrated based on past losses, and then modelled using multiple regression analysis. It also provided a vulnerability proxy in the form of a ratio of observed killed per average exposed per year [10,66,67]. Risk was calculated at the national level. The main message of this UNDP report was that poverty kills.

However, poverty is not the only vulnerability factor. The 2003 heatwave took European countries by surprise, killing more than 84,000 people (according to EMDAT) and generating high economic losses [68]. It was a reminder that developed countries are not immune from large disasters triggered by natural hazards. This was further demonstrated with hurricane Katrina (USA) in 2005, and the Fukushima earthquake, tsunami, and nuclear accident in 2011 in Japan (see below).

At the end of 2004, the Indian Ocean tsunami devastated thousands of kilometers of coast, mostly in Indonesia, Thailand, India, Sri Lanka, and the Maldives, but also as far away as Kenya and Seychelles, killing more than 226,000 people (according to EMDAT).

The Kobe Conference was held three weeks after the Indian Ocean tsunami disaster. The magnitude of the disaster galvanized the willingness of the international community, with 168 countries endorsing the first global framework on disaster risk reduction, known as the Hyogo Framework for Action (2005–2015): Building Resilience of Countries and Communities (HFA). Encompassing five priorities of action, the HFA set out the roadmap for safer societies in the decade that followed [69].

In 2005, the World Bank launched the report entitled "Natural Disaster Hotspots: A Global Risk Analysis" [70] (Dilley et al., 2005), with the first global estimation of economic risk and human loss at the sub-national level, albeit with a coarse resolution. It included an assessment for six hazards (drought, tropical cyclones, floods, earthquakes, landslides, and volcanoes). The primary focus was to identify areas/regions that have been affected by these multiple hazards. Both the UNDP and World Bank reports [10,70] were pioneers in modelling exposure to hazards at a global level.

Another interesting report on disaster risk was published in 2005, which introduced new methodologies developed for South American countries [71]. However, though these three reports [10,70,71] contributed to a better understanding of risk, risk trends, and their distribution at the global level, none of them took climate change into consideration in the estimation of risk.

Meanwhile, the year 2005 broke previous temperature records in the northern hemisphere, and tropical cyclones reached an unprecedented frequency. With a total of 28 storms over the northern Atlantic, the year greatly exceeded the previous record (of 21 storms) reached in 1933. Of the 28 storms, 15 became tropical cyclones and 7 became supercyclones [72]. The year 2005 had the highest economic losses from climatic events, totaling US $200 billion in losses. Hurricane Katrina alone amounted to US$125 billion. Hurricane Wilma had the strongest winds and the lowest central pressure ever recorded (gusts of winds reaching 330 km/h and a lowest central pressure of 882 hPa) [72]. With the all-time record reached in the frequency and intensity of tropical cyclones in 2005 and the 2003 heatwave, the idea that climate change may be influencing hazards and extreme events was gaining broader public recognition. Stott and Allen [73] showed that severe heatwaves, such as the one in 2003 in Europe, had twice the probability of occurring due to anthropogenic impacts on climate. Hurricane Patricia (2015), with a central pressure of 872 hPa, the highest 1 minute sustained wind speed (245 km/h), and a peak intensity of 95 m/s (342 km/h), set a new record for the North Atlantic and eastern Pacific regions [74].

The years 2006–2007 spurred a large momentum of concern about climate change amongst the general public and governments, which was marked by three different milestones. The Stern Review Report: the Economics of Climate Change [75] captured the attention of the economic community. The IPCC's Fourth Assessment Report [50] had a significant influence on policymakers, governments, and the scientific community. Finally, the movie "An Inconvenient Truth", featuring Al Gore [76], contributed to a wider diffusion of the message on climate change to the general public. The IPCC's and Al Gore's works received worldwide recognition, when they became joint recipients of the Nobel Peace Prize in 2007.

In 2009, UNISDR produced their first Global Assessment Report on Disaster Risk Reduction (GAR) [11]. This report includes a chapter on global risk analysis, which solved some of the main methodological issues faced in previous global risk assessments. The GAR included new hazard models for tropical cyclones [63], landslides [77], droughts, and tsunamis [78], and the first global flood model at 90 meters resolution [79], as well as a re-interpretation of earthquake realized risk. The GAR allowed for the computation of human and economic exposure. The new methodology applied an "event per event" approach, which facilitated taking hazard intensity into consideration [63,80]. All these models could be visualized, interrogated, and downloaded through the PREVIEW Global Risk Data Platform [81]. Risk maps were computed for four natural hazards (floods, earthquakes, landslides, and tropical cyclones) at a 1 × 1 km resolution, and delivered at a 5 × 5 km resolution. These were aggregated at the country level to produce the Mortality Risk Index (MRI). Results showed that the intensity of hazard, level of exposure, poverty, and bad governance were the main underlying factors of risk. It further demonstrated that geographical remoteness in the case of flood risk, and rapid urban growth linked to poor governance in the case of earthquake risk, were aggravating factors of risk. Vulnerability was found to be the main contributor to mortality in the case of low intensity hazards, while exposure was the main factor in higher intensity hazards [63,80].

The subsequent Global Assessment Report on Disaster Risk Reduction published in 2011 [12] reapplied the risk models used in GAR 2009 for different time periods from 1970 to 2010. The risk trend analysis showed that, while mortality risk was decreasing due to a significant decrease in vulnerability to hydro-meteorological hazards, economic risk was increasing [12]. Vertical urbanization (e.g., in China) was one explanation. Additionally, the improvement in early warning systems facilitated evacuation of exposed populations but offered no protection to infrastructure. This explains why, in some regions, mortality is decreasing at the same time that economic risk is increasing [12] The GAR 2013 [82] focused on economic risk, and continued the development of new methodologies based on probabilistic hazard modelling and stochastic risk evaluation. This was achieved for earthquakes and tropical cyclones; the model for floods was completed for GAR 2015 [83].

In 2015, three major new agreements were reached to improve the global environmental governance, which all have a clear focus on reducing disaster risk. A new Sendai Framework (2015–2030) includes seven goals. The post-2015 development agenda with the 17 Sustainable Development Goals (SDGs) were signed, and the Climate COP21 in Paris set an ambitious agenda for the parties, by setting the aim of maintaining the temperature between 1.5 °C and 2 °C above pre-industrial levels.

The role of ecosystems in climate change adaptation and disaster risk reduction is well recognized by and highlighted in these three agreements.

These new international frameworks are very ambitious and give a clear and legitimate mandate for many development agencies, research institutions, and governments to take new action toward sustainable development. The four communities (climate, risk, environment, and development) are gradually gaining in mutual understanding and starting to work together (see Figure 3). This was the case, for example, when the risk and climate scientific communities jointly produced the IPCC Special

Report on Extreme Events [13]. They found a common terminology and, since this report, IPCC has adopted the risk framework from UNDRO [6].

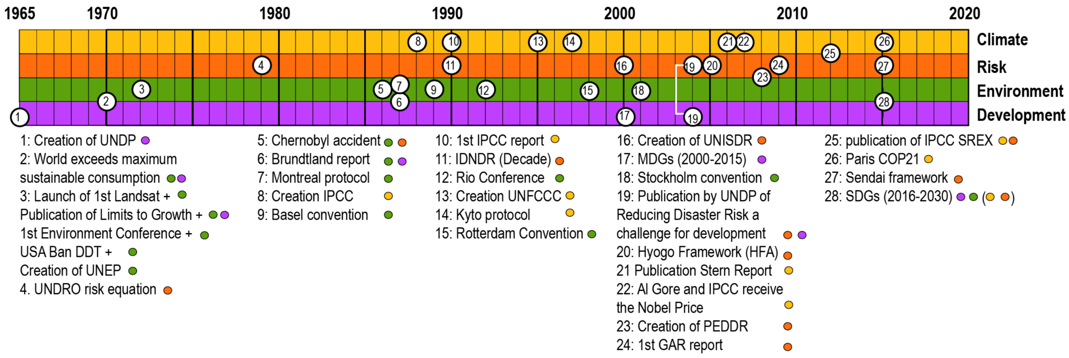

Figure 3. Main milestones cited in this article. New frameworks were added through time. Development (1960s), Environment (1970s–1980s), Climate (1990s) and Risk (2000s) are shown to be slowly getting closer to each other (after 2005).

3. Disaster Risk Exacerbated by Global Change

This review retraces some of the progress made in the last 50 years of advancing toward the recognition of the inter-connectivity of various processes linked with disaster risk. It shows that the recognition of disasters as compound events took decades. However, there is now more than enough scientific understanding to take action. In terms of climate change, the third IPCC assessment report (AR) stated that the anthropogenic influence of climate change was likely (>66%), the fourth IPCC AR said it was very likely (>90%), and the fifth IPCC increased this level of confidence to extremely likely (>95%). There is no need for a higher confidence level. The Paris agreement states that global emissions should peak at 52 $GtCO_2e$ by 2020, then be reduced at 42 $GtCO_2e$ (29–44) in 2030, to achieve net zero emissions by 2060 (2060–2075), after which negative emissions (through reforestation, for example) will be needed between 2060 and 2100 (-11 $GtCO_2e$ for a 66% chance of staying below 2 °C). Time is ticking and the speed of action is not fast enough for this race against climate change. The probability of remaining below 1.5 °C, or even below 2 °C, were estimated at 1% and 5%, respectively [84].

Over the past two decades, there has been increased acceptance that disasters are mostly man-made and that only the hazard component of disaster risk is natural. Now, even this last statement is being challenged.

3.1. *The Unnatural Side of Natural Hazards*

3.1.1. Risk and the Impacts of Climate Change

Aside from tectonic hazards (e.g., earthquakes, tsunamis, or volcanic eruptions), human activities can exacerbate natural hazards. By emitting Green House Gases (GHG), human activities are changing the climate and, as a result, climate-related hazards [50].

In 2012, the IPCC Special Report on Extreme Events was published [13]. It confirms that several hazards will be exacerbated by climate change, which is likely to affect hydro-meteorological hazard patterns, their frequency, their intensity, or even their spatial distribution and extent [13]. For example, tropical cyclones are likely to be no more frequent but are likely to be more severe, depending on the specific tropical cyclone basins. The maximum intensity of tropical cyclones is migrating poleward at about 1° latitude per decade [85]. Heatwaves will very likely be more frequent. The frequency of heavy precipitations is likely to increase. Drought is expected (with medium confidence) to intensify. Sea level rise is very likely to contribute to upward trends in extreme coastal high water levels in the future. However, the authors of the report agree that the main driver of risk is the increase in exposure (i.e., increase in population and infrastructure density). Despite a forecast reduction of tropical cyclone frequency, the combination of higher tropical cyclone intensity and population growth will lead to increased exposure to tropical cyclones, and at a higher intensity [63].

3.1.2. Risk and Ecosystem Decline

Transformation of the natural environment also impacts natural hazards. By deforesting slopes and building roads, humans are increasing susceptibility to landslides [86,87]. Paved roads and urban expansion are "waterproofing" soils, thus reducing water infiltration [12]. Inadequate drainage to cope with excess run-off is increasing the occurrence of urban floods [88]. Fires are used for slash and burn practices and for converting forest to cropland; these practices are responsible for the majority of biomass fires [23]. At the same time, drier conditions are leading to more forest fires [89].

Ecosystem decline, such as deforestation and destruction of coastal and marine ecosystems, is exacerbating the impacts of natural hazards [11]. In some cases, they influence susceptibility to the hazard itself directly, for example by reducing natural protection, leading to higher intensity of waves and storm surges, and thus to worsening coastal flooding [90] and beach erosion [91]. Deforestation exacerbates flood severity [92], landslide susceptibility [86,87], droughts, and wildfires [89].

The links between slow-onset but continuous hazards and global disaster risk have been insufficiently studied. Moreover, the loss of ecosystem services and the impact of this on disaster risk remains a serious knowledge gap. Research in this area may be catalyzed by the emergence of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). Ecosystems can be used for disaster risk reduction [93,94]. In some places, ecosystems can be combined to reduce the need for grey infrastructure [95].

3.1.3. The Nat-Tech Nexus: A Clear Compound Event

The Fukushima nuclear accident following the Great Tohoku Japan earthquake and tsunami in March 2011 was a game changer. This catastrophic event demonstrated that secondary effects of natural hazards can have broader consequences than the initial triggering event. These can lead to technological or industrial disasters, increasingly referred to as the "Nat-Tech" nexus [12]. The Government of Japan recognized that the nuclear accident was clearly a man-made disaster, a result of collusion between the government, regulators and TEPCO—the company managing the Fukushima nuclear power plant—but the technological disaster was initially triggered by a powerful earthquake and subsequent tsunami [96].

Germany, Switzerland, and Japan have taken the lessons from Fukushima, deciding to gradually withdraw from nuclear energy [97]. The consequences of nuclear disasters are on a unique time-scale, with long-lasting impacts. When comparing the aftermath of the 2004 Indian Ocean tsunami and the 2011 Japan tsunami, the first event triggered the third largest disaster in terms of mortality since 1975, while the latter event triggered record economic losses (according to EMDAT). However, the main distinction between these two events lies in the difference in the duration of their impacts. Two years after the 2004 Indian Ocean tsunami, touristic infrastructure in Thailand was largely rebuilt [98]—even as quickly as within one year on Phuket Island [99]. In Japan, after two years, there were still 160,000 evacuees, and there are still major radioactivity leaks from the nuclear power plant, with the decontamination of the site expected to take decades [100]. Another difference between a nuclear accident and a natural hazard-induced disaster is the feasibility of intervention. Radioactivity makes direct intervention to mitigate impacts extremely difficult, and at the expense of the health of workers [101]. A nuclear accident prevents large areas of land being used by humans over an extended time period.

The Fukushima nuclear accident was considered a "game changer" because, until then, we thought that vulnerability was mostly an unresolved issue of development [10,11]. Fukushima revealed that development could lead to different vulnerabilities, and lead to multiple risks.

Tsunamis are not the only natural hazards to place Nuclear Power Plants (NPPs) under threat. NPPs have been shut down during droughts and heatwaves, due to lack of water or temperatures being too warm in river waters, preventing adequate cooling of the NPP reactors [68]. Heavy snow falls, floods, freezing temperatures, and even jelly fish [102] have been known to force NPPs to shut down.

NPPs and other critical facilities are not the only concerns for Nat-Tech hazards. For instance, floods have led to the pollution of rivers [94,103]. However, the reverse is also true. The recent (25 January 2019) burst of tailings dam at iron ore mine, which led to the release of a wave of red sludge, flooding and killing unknown number of people (still hundreds reported missing at the time of publication) in the state of Minas Gerais (Brazil). Or the uncontrolled discharge of 70 million tonnes of waste rock and mine tailings annually have spread more than 1000 km down the Ok Tedi and Fly rivers in Papua New Guinea, raising river beds and causing flooding, sediment deposition, forest damage, and a serious decline in the area's biodiversity [47].

Despite Fukushima, the nexus between natural and technological hazards that creates Nat-Tech disasters is not well-studied by the disaster risk community, and remains a knowledge gap. It should be better studied and mainstreamed into local land-use planning, contingency planning, and disaster management policies.

3.2. Mainstreaming Global Change in the Research and Policy Agendas

Risk is dynamic in nature. Increases in population and building of infrastructure have raised the exposure to natural hazards [11,12]. Climate change and ecosystem decline are inducing changes in hazards' susceptibility, coverage, frequency and severity [13]. Most of the underlying drivers are related to global change. With the IPCC Special Report on Extreme Events [13], climate change began to be considered appropriately in global disaster risk.

There are two biases in global disaster risk research. The first is that risk of economic losses and mortality losses do not have the same distribution. While developed and developing countries have similar levels of exposure to natural hazards (15% and 11%, respectively), mortality risk varies tremendously, with developed countries recording an average 1.8% mortality risk, and developing countries 53% [10,67]. Research using economic risk to prioritize adaptation [104] shows different risk patterns, and tends to favor protections in highly developed countries, whereas mortality risk mapping highlights poor countries [10,11,83,105]. These different approaches have led to different messaging priorities [105]. Economic risk is well funded (e.g., by insurance), and the mathematics are in a way easier than for mortality risk, because unlike population, which can be evacuated to a safe area, infrastructures stay, and impacts on them or on their content has a replacing/rebuilding price and follows the rules of physics, which are well understood in structural engineering. Mortality risk is more chaotic, as it is more complex to assess human behavior and human vulnerability. Behavioral science shows that intuitive thinking plays a strong role, and is influenced by things such as past flood experience [106]. Additionally, the issue is not only about the number of deaths, but about how to re-organize the livelihoods of the survivors.

The second bias is that research tends to focus largely on hazard modelling, while the underlying factors are still not well addressed. The hazard component is the best covered. There are several global tropical cyclone hazard models, which include scenarios for climate change [63,82,107]. The Global Earthquake Model (GEM) (see http://www.globalquakemodel.org/). The Global Volcano Model (GVM) (see http://www.globalvolcanomodel.org/) has been initiated by a consortium of research institutions. Several global flood models have been developed [108], ranging from 90 m resolution [79,109] to 1 km resolution, and including climate change forcing [110]. Global landslide models continue to be refined, and are now aiming at including deforestation [11,77,82]. Tsunami models are nearing global coverage [78]. Large improvements have been made in improving global exposure datasets, mainly thanks to GEM and GAR efforts. A new global exposure model is now available for economic risk modelling [111]. However, vulnerability is still the most difficult component to assess, especially regarding human vulnerability [13,16–18,63,67]. There are two products looking at global fire scars; one using SPOT Vegetation [44], and the other based on the MODIS sensor [112]. However, these two products do not correspond to one another [113]. Most of these datasets are made freely available through the PREVIEW Global Risk Data Platform [81].

Disaster risk is only one portion of all environmental risks, and in terms of mortality, is much smaller than other threats. For instance, globally each year 7.6 million people die from cancers (including 1.3 million from lung cancer alone). According to the World Health Organization (WHO), malaria kills a child every 30 seconds and accounts for one million deaths per year. Outdoor air pollution claims 3.3 (1.61–4.81) million premature deaths per year worldwide [114]. This calls for a more global approach to the overall improvement of living conditions in the political agenda.

Already, at the 6th special session of the United Nations Environment Programme Governing Council in 2000, the Ministers of Environment and heads of delegation identified the major environmental challenges of the twenty-first century, as follows:

> "Environmental threats resulting from the accelerating trends of urbanization and the development of megacities, the tremendous risk of climate change, the freshwater crisis and its consequences for food security and the environment, the unsustainable exploitation and depletion of biological resources, drought and desertification, uncontrolled deforestation, increasing environmental emergencies, the risk to human health and the environment from hazardous chemicals, and land-based sources of pollution, are all issues that need to be addressed." [115]

However, these long-term issues tend to be side-lined. Modern journalistic practices tend to overemphasize the most spectacular deaths. The space dedicated in the media to mortality is not proportional to the number of deaths [116]. Illicit drugs, motor vehicles, toxic agents, and homicide are overrepresented [117]. Other less common factors linked to mortality, such as SARS and terrorism, are likewise proportionally overrepresented in the media. On the other hand, the main causes of mortality, such as AIDS, physical inactivity, and smoking, are inversely underrepresented [118].

For the media, it is difficult to make headlines that feature continuous environmental degradation and, in their uphill struggle to keep readers' and viewers' attention, issues related to global change are often relegated to the scientific pages. However, such topics are more complex than can be expressed by simple statements [118]. If Meadows, Turner, Randers, Rockström, Steffen, and others are correct, the threats from global change to humanity are larger than we realize, and contribute to increasing disaster risk [25,30,61,62,119]. How to keep people interested in slow but continuous processes remains a serious challenge.

Humans are poorly equipped to deal with slow onset processes. Researchers call this category of environmental change "creeping changes" [120]. These incremental changes are unnoticed until they pass a threshold and quickly lead to changes in the environment, or are revealed by a sudden onset hazard [21]. Biodiversity loss, climate change, desertification, stratospheric ozone depletion, tropical deforestation, mangrove and coral destruction, soil erosion, soil and water pollution, overfishing, and invasive species all fall into this category of slow on-set processes, which are continuously destabilizing the Earth system on which we depend.

Creeping changes are often overlooked, because we think we can deal with them later on, or because they are in opposition with current ways of running business, where economic growth is still the main concern for governments and company leaders.

4. Conclusions

The risk framework for understanding risk has greatly evolved. From hazard mapping, we have progressed through the introduction of socio-economic factors in vulnerability. Then, the development community presented risk as an unresolved question of development [10]. The risk complexity continued to unfold after the Fukushima nuclear accident (2011), unveiling that high-tech countries were generating their own risk with Nat-Tech hazards. This brought a new perception of risk as being designed, and the idea that disasters cannot be considered as being natural anymore. Furthermore, the climate change and environmental change scientific communities have now demonstrated that even the natural hazard is not only natural. Anthropogenic climate and environmental changes are also affecting risk. As the complexity of risk unfolds, we have discovered its multiple dimensions. The risk framework is being studied by experts from multiple backgrounds. The risk community, initially emerging from civil protection, has gradually incorporated civil engineers, land planners, social scientists, economists, development experts, and climate and environmental scientists. This list may continue to grow. This is bringing risk to a more holistic framework, as shown by Figures 2 and 3. However, a difficulty remains for experts coming from a specific background to recognize and understand the role of other disciplines, and not everyone is open to interdisciplinary cooperation, or is able to think outside the box.

Perhaps because of this, the environmental dimension of risk has not yet been fully integrated into main global agencies (UNISDR, the World Bank), or into insurance models.

These organizations are still mostly focusing on sudden disasters, and do not yet include creeping hazards. Soil erosion and its associated impacts on flooding, landslides, and the siltation of water courses are usually cheaper to fix and easier to deal with in their early stages. If we wait too long, the costs of mitigating the environmental impacts and associated disaster risk may become prohibitive, and even not technically feasible anymore [120–123]. They can build up over time and lead to global impacts, or reach tipping points after which a no-return situation is reached. This may be the case already in the irreversible melt of the Greenland ice sheet, dieback of the Amazon rainforest, and the shift of the West African monsoon [123,124]. It is important to highlight the role of creeping change in increasing risk to human societies, and not only look at risk from natural hazards.

Some impacts of these creeping changes may not be linear, but may include tipping points, after which drastic changes may occur [125]. Such behavior, with sudden and abrupt transitions, affects complex dynamical systems such as ecosystems (lakes, wetlands, and pollinators) [126–128], and also economic, social, and infrastructure systems [126]. The sudden onset of these phenomenon has limited early warning [126]. The main agencies working on DRR should give more importance in their programmes to these creeping changes, and to the phenomenon of tipping points, as they can potentially lead to major and drastic consequences or even collapse [30,119]. Methods for assessing ecological tipping points [129,130] can be used to convince decision makers. Glantz [120] and other researchers believe this would require a rapid shift in the focus of environmental policy; specifically, the inclusion of new, early environmental monitoring followed by quick action. Lenton and others [123] highlight the need for institutional systems that have an improved capacity for real-time monitoring, such as those with effective signal detection and precise predictions. They also emphasize the need for backward extrapolation of existing monitoring data to develop better predictive models, and anticipate creeping changes.

Studies have shown that focusing only on environmental impacts from human activities is less effective in influencing changes in policy [131]. The use of ecosystems for adaptation to climate change and DRR may provide the “no regret” option, because of the multiple benefits provided by ecosystems [93,131]. Understanding how ecosystems may mitigate impacts from climate change [91,132]. These are important contributions towards proposing solutions to reduce disaster risk. The Partnership for Environment and Disaster Risk Reduction (PEDRR), a global alliance of UN agencies, NGOs and specialist institutes, has already started to compile examples [93,133].

To achieve this new perception of risk, it was necessary to raise awareness. Many of the cited research papers were designed to demonstrate the role of social, development, climate, or environmental factors as direct or underlying factors leading to higher risk. In my view, the new direction of research should focus on solutions, which should then be rapidly implemented. The current environmental changes have now, due to long lasting negligence, reached a serious level of global impact and nuisance.

Addressing these global environmental concerns will require a large number of experts and specialists [134–137], which will need to be trained (e.g., in renewable energy, water, sustainable agriculture, forestry, fisheries, architecture, and land planning) on integrated risk management in the context of development planning. Education systems need to be upgraded to take these needs into account [137].

The complexity of compound events has led to several decades of delay in appraising the interconnectivity amongst social, economic, climate, and environmental drivers.

The new international frameworks (Sendai 2015–2030, COP21, and the post-2015 agenda) have set ambitious targets. We urgently need to implement them over the next few years, as achieving disaster risk reduction is closely linked with achieving sustainable development.

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