



Understanding systemic risk induced by climate change

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Received 30 October 2020; revised 20 May 2021; accepted 24 May 2021

Available online 1 June 2021

Abstract

The systemic risk induced by climate change represents one of the most prominent threats facing humanity and has attracted increasing attention since the outbreak of the COVID-19 pandemic at the end of 2019. The existing literature highlights the importance of systemic risk induced by climate change, but there are still deficiencies in understanding its dynamics and assessing the risk. Aiming to bridge this gap, this study develops a theoretical framework and employs two cases to illustrate the concept, origin, occurrence, propagation, evolution, and assessment framework of systemic risk induced by climate change. The key findings include: 1) systemic risk induced by climate change derives from the rapid growth of greenhouse gas emissions, increasingly complex connections among different socioeconomic systems, and continuous changes in exposure and vulnerability; 2) systemic risk induced by climate change is a holistic risk generated by the interconnection, interaction, and dynamic evolution of different types of single risks, and its fundamental, defining feature is cascading effects. The extent of risk propagation and its duration depend on the characteristics of the various discrete risks that are connected to make up the systemic risk; 3) impact domains, severity of impact, and probability of occurrences are three core indicators in systemic risk assessment, and the impact domains should include the economy, society, homeland security, human health, and living conditions. We propose to deepen systemic risk research from three aspects: to develop theories to understand the mechanism of systemic risk; to conduct empirical research to assess future risks; and to develop countermeasures to mitigate the risk.

Keywords: Systemic risk; Climate change; Disaster; Risk assessment

1. Introduction

In the past five decades, the global climate system has experienced significant changes in most parts of the world, as manifested by increasing frequency, intensity, and impacts of extreme weather events. As the whole world enters the stage of a ‘risk society’ (Beck, 1992; Giddens, 1999), it has become a general consensus that risk induced by climate change represents one of the most prominent threats facing humanity

(Deere-Birkbeck, 2009; Stern, 2015). The release of the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) by IPCC (2011) has drawn interesting scholarly attention to climate risks. In contrast to conventional risks whose impacts are usually bounded and limited, the risks of climate change are systemic (King et al., 2015). Although the direct impact of climate change is local, it can have knock-on effects across regions and sectors, through interconnected socioeconomic and financial systems, which are secondary risks generated by the propagation of direct risks in the human system (CEPCC and UKCCC, 2018; MGI, 2020; Rosa et al., 2013). The greatest climate risks may arise from the interaction between

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Peer review under responsibility of National Climate Center (China Meteorological Administration).

climate and complex human systems such as global food markets and national and international security.

Risk is herein broadly defined as “the likelihood that an undesirable state of reality (adverse effects) may occur as a result of natural events or human activities” (Renn, 2008). This definition distinguishes risk from risk events, which have the potential to trigger such risks. The concept of systemic risk was first introduced by OECD (2013) in the final report of The Futures Project on Emerging Systemic Risks to refer to risks that affect the systems on which society depends, such as health, transport, and the environment. The term ‘systemic’ is meant to capture the embedded nature of the risk in the larger context of societal processes (Asselt and Renn, 2011). According to Kaufman and Scott (2003), it is “the risk that the entire system may break down, as opposed to the breakdowns in individual parts of components”, and “the co-movements (correlation) among most or all parts”, that distinguish systemic risk from other types of risks. Systemic risk may be triggered by a direct risk or consists of a bundle of several different risks (King et al., 2015). Systemic risk is an unintended, often-ignored side-effect of globalization, which has generated a new and unprecedented level of interdependence and complexity in the social systems, particularly in the 21st century (Centeno et al., 2015; Goldin and Vogel, 2010), hence the four major properties of systemic risk: 1) global in nature, 2) highly interconnected and intertwined leading to complex causal structures, 3) non-linear in the cause–effect relationships, and 4) scholastic in their effect structure (Renn, 2016). Systemic risk exemplifies all three characteristics of risk problems: complexity (difficulty of identifying and quantifying causal links between a multitude of potential candidates and specific adverse effects), scientific uncertainty (limitedness or even absence of scientific knowledge required to assess the probability and outcomes of undesired effects), and sociopolitical ambiguity (the existence of multiple values and perspectives) (Klinke and Renn, 2002; Renn et al., 2011, 2018). Because of the wide impacts of systemic risk and its complex internal connections, systemic risks are nearly irreversible once a risk-triggering event has occurred and the tipping point crossed, and possess the potential to do more harm compared to single risks and to pose serious threat to the structure and function of the human society (Asselt and Renn, 2011; Renn, 2008). Therefore, preventive measures must be taken in the first place.

Historically the term systemic risk has only referred to collapses in the financial sector (Goldin and Vogel, 2010), which is claimed to be more vulnerable to systemic risk than other sectors of the economy due to the structure of bank balance sheets, the complex network of exposures among financial institutions, and the intertemporal character of financial contracts and related credibility problems (de Bandt and Hartmann, 2000). As a result, the majority of the extant empirical studies on systemic risk has focused on the financial sector, particularly in understanding the causes and mechanisms of the financial crises, such as the global financial crisis in 2008 (Brunnermeier and Oehmke, 2013; Harrington, 2009). Scholars have documented historical evidence of contagious

systemic risk in banking (Kaufman and Scott, 2003), developed a large variety of quantitative measures of systemic risk (Acharya et al., 2016; Bisias et al., 2012; Huang et al., 2009), and modeled the propagation of shocks within financial systems drawing analogies with the dynamics of ecological networks (Haldane and May, 2011). The study on systemic risk in the financial market exposes the profound, structural shortcomings of modern global institutions to cope with new global systemic risks in the 21st century, which stemmed from a lack of understanding of systemic risk, and calls for global coordination and collaboration (Goldin and Vogel, 2010).

Compared to systemic risk in the financial sector, other types of systemic risk, such as that induced by climate change, are even less understood (Goldin and Vogel, 2010). Recent years have witnessed an emerging, albeit still limited, literature on systemic risks induced by climate change. For instance, both the U.S. Third National Climate Assessment (Moser et al., 2016) and the UK 2017 Climate Change Risk Assessment (Challinor et al., 2017) look into cross-border climate risk, i.e., how climate impacts in other countries or regions affect the domestic economy and territory. In particular, the former highlighted the cross-border risks for neighboring countries with shared water resources. The latter identified transboundary risk transmission mechanisms and systematically assessed risks posed by climate change globally to the UK, such as the negative impact of weather-related shocks to international agricultural production and food supply chains on food prices and accessibility for vulnerable groups, as well as the impact of climate-related displacements of populations worldwide on the UK (Challinor et al., 2016, 2018). In the context of China, one of the best-known works along this line is the UK–China Cooperation on Climate Change Risk Assessment: Developing Indicators of Climate Risk co-authored by China Expert Panel on Climate Change & UK Committee on Climate Change (CEPCC and UKCCC, 2018), which assesses several typical systemic risks induced by climate change from both a national and a global perspective, for instance the systemic risk in the global food system. The outbreak of the COVID-19 pandemic in the end of 2019, which has either generated or contributed to a series of interconnected financial, societal, and political crises on a global scale, has triggered comparative studies of systemic risks of pandemics and climate change, which share many commonalities despite differences (Pinner et al., 2020).

Systematic risk induced by climate change can be broadly classified into emergency risk and incremental risk based on different latent periods and manifestations (CEPCC & UKCCC, 2018). Emergency risk often arises from a shock event, also known in the literature as a ‘black swan’ event. Such risks are hard to predict and can have catastrophic impacts. Extreme weather events are typical examples that may pose emergency risk. For instance, the outbreak of Hurricane Sandy in the Americas in 2012, which swept over Cuba, Dominica, Jamaica, the United States and other countries, caused more than 60 billion USD in damage and 233 casualties, leading to severe impacts on energy, transportation, and financial systems (Diakakis et al., 2015; Strauss et al., 2021).

In China, one recent case is the heavy rain that happened in Beijing on July 21, 2012, which caused the collapse of 10,660 houses, affected 1.62 million people and caused an economic loss of 11.64 billion RMB (Hou, 2012). The occurrence of disasters caused by emergency risks depends on the ‘disaster inducing threshold’ of the system, which is closely related to the system's exposure and vulnerability. Under the same weather and climate conditions, the higher the exposure and vulnerability of the system, the lower the disaster inducing threshold and the higher the probability of a disaster.

Incremental risk displays typical creeping characteristics and the fat tail effect. Since changes take place rather slowly, the adverse consequences take a long time to emerge. However, the huge potential impacts and long-term consequences are easily underestimated in the early stage, hence the Chinese old saying “one ant hole may cause the collapse of a thousand-mile dyke (*qian li zhi di kui yu yi xue*).” Incremental risk therefore often arises from ‘grey rhino’ events. Compared with the unpredictability and sporadic occurrence of a black swan event, a grey rhino event is not a random incident, but a high-probability event that occurs following a series of signs and warnings. Once incremental risks cross a critical point, they are difficult to manage. Most climate change-induced systemic risks are incremental risks. Climate impacts will accumulate and worsen over time and across space. They usually go through a process from quantitative change to qualitative change, which eventually leads to the outbreak of a disaster. A typical example of incremental risk is the risk of water shortage in Africa, which reduces food production over time and aggravates malnutrition and other health problems, leading to migration and regional violent conflicts.

In general, the main contribution of the extant literature on systemic risk induced by climate change, albeit limited, is to put forward the concept of systemic risk and to clarify the differences and connections between systemic risk and other types of risk. The literature also qualitatively assesses several typical systemic risks individually, such as water resource security risk and urban security risk. However, there still exists a gap between the existing literature and a complete conceptualization of systemic risk induced by climate change, let alone potential ways to mitigate it. Therefore, this study aims to partially fill the gap by integrating and refining the existing fragmented knowledge about systemic risk induced by climate change into a complete theoretical framework so as to present a holistic picture of systemic risk. Specifically, this study analyzes the dynamics of systemic risk induced by climate change and develops a framework to assess it. The study also uses two typical cases of systemic climate risk to illustrate the assessment framework.

2. Research framework

The risk governance theory usually divides risk governance into risk assessment and risk management (IRGC, 2005). Risk assessment is a comprehensive understanding of risk, including risk identification, risk analysis, and risk evaluation,

while risk management is a series of decisions and actions made based on a complete understanding of risks. This study does not involve risk management and focuses on understanding risk. The study decomposes climate risk into four specific questions, namely, why does systemic risk occur? How does systemic risk occur? How does systemic risk propagate and evolve? How to assess systemic risk? The first three questions involve the dynamics of systemic risk, and the last question is related to risk assessment.

Focusing on the four key questions above, the study establishes an analytical framework (Fig. 1). The study understands systemic risk through theoretical and empirical perspectives. The theoretical research employs methods including theoretical analysis, literature review, brainstorming, and case study. The fundamental theories of this study are derived from IPCC's climate risk theory (IPCC, 2011), system ecology theory (Odum, 1983), and risk assessment theory (IRGC, 2005). The climate risk theory elaborates the formation mechanism of climate risk from the perspectives of extreme weather and climate events (also known as hazard factors), exposure, and vulnerability and expounds on the particularity of climate risk relative to general risk. By analyzing the structure and function of the ecosystem, system ecology explains the influence of ecological disturbance on a complex system, expounds the stability mechanism of the ecosystem, and develops the theory of resilience, which provides an essential reference for understanding systemic risk. Risk assessment theory expounds on the process and content of risk assessment and provides a general framework for systematic risk assessment. The above theories provide a theoretical basis for understanding systemic risk induced by climate change. The existing literature and cases also contribute to the theoretical analysis as the basis of research. The study takes brainstorming as an essential research method. It draws on constructive suggestions from Tsinghua University, Energy Research Institute of the National Development and Reform Commission, the Chinese Academy of Social Sciences, the Chinese Center for Disease Control and Prevention, National Meteorological Administration, and other institutions. Based on theoretical research, the study adopts the case study method to develop a practical perspective for understanding systemic risk.

3. Dynamics of systemic risk induced by climate change

3.1. The origin of systemic risk

Systemic risk induced by climate change has three basic characteristics: 1) the wide scope of climate change impacts, affecting a wide range of natural, economic and social systems; 2) the long duration of climate change impacts; and 3) cumulativeness of these impacts, that is to say, these impacts will grow over time. Therefore, a systemic climate risk usually takes years to form.

The formation of a systemic climate risk can be triggered by the following reasons. First, the rising greenhouse gas

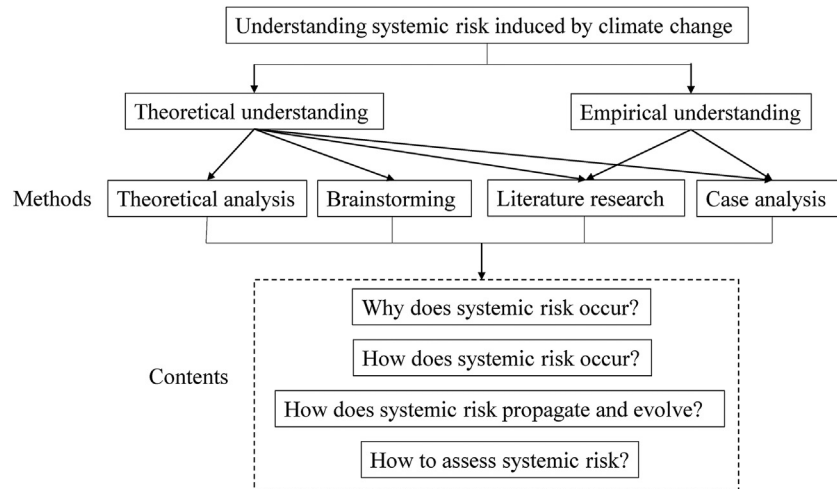


Fig. 1. Research framework of the study.

emissions increase the likelihood of more dramatic climate change. Meteorological evidence shows that since the Industrial Revolution, the concentration of carbon dioxide in the atmosphere has increased from about 280×10^{-6} to about 400×10^{-6} , and the average surface temperature has increased by 0.85°C (IPCC, 2015). Even under the low emission scenarios, carbon dioxide concentrations will rise to 450×10^{-6} by the end of the century, and average surface temperatures will rise by 1.5°C , posing greater climate risks (IPCC, 2015). Second, there is a lack of adequate adaptation to climate change, as a result of which climate impacts are accumulating over the year. Third, exposure and vulnerability of human, economic and social systems are constantly evolving. Research shows that by 2050, world population would reach 9.7 billion, within which senior people aged 65 years or above may surpass adolescents and youth aged 15–24 years (UN, 2019). Last but not least, the increasingly complex connections among human systems constitutes a complex network. Once a link in any system collapses, it is likely to trigger a systemic reaction.

3.2. The occurrence of systemic risk

A systemic climate risk is triggered by one or more direct risks caused by climate change, and then has cascading effects at economic, social, cultural, ecological and political levels. When cascading effects take place, one risk causes one or several risks, which then propagate further. According to the complexity of cascading effects, they can be divided into series effects and parallel effects (Fig. 2). Series effects refer to a causal chain where one risk causes the formation and occurrence of another indirect risk, also known as series risk. Parallel effects refer to a causal chain where one risk causes the formation and occurrence of multiple risks, also known as parallel risk. Systemic risk is often triggered by a direct risk, and then forms a series of indirect risks through cascading effects, affecting the structure, function and stability of the whole system. Cascading effects are the defining, fundamental characteristic of systemic risk that distinguishes it from direct risk.

The objective of systemic risk analysis is to investigate the interconnections, causal chains and feedback loops among different impacts and to evaluate the probability of cascading effects and their potential consequences. In modern economic and social systems, the various elements are more closely connected and their relationships more complex, which constitute a large complex system. In contrast to cascading effects, in many cases, indirect risks are caused by the interaction between multiple related risk factors. In other words, there may be multiple causes for one result, or there may be multiple causes for multiple results, which are referred to as bundling effects. In the real world, cascading effects and bundling effects often occur at the same time. A nexus risk happens when two or more types of risks are associated and interact with each other.

There exist two types of feedback loops, i.e., positive feedback loop and negative feedback loop, in a causal chain of risks. A positive feedback loop accelerates and amplifies systemic responses. When one part of the loop is damaged, it can cause a disruption or even a breakdown of the entire system, hence creating a vicious cycle. A positive feedback loop may also create a virtuous cycle, making the system function more in line with people's needs. On the other hand, a negative feedback loop can offset the adverse effect of the higher-order risk, so that the system tends to stabilize. In a systemic risk with a vicious cycle, it is often possible to identify a quantitative index. When this index is within a certain threshold, system balance can still be restored through the adjustment of negative feedbacks. However, once the threshold is breached, it is often too late to change the situation, leaving the vicious cycle to dominate the evolution of the whole system until it collapses. The threshold of a system is also called a tipping point. Establishing indicators, thresholds or critical points is very important in systemic risk analysis. In addition, the weak points within a system require particular attention.

3.3. The propagation and evolution of systemic risk

IPCC (2011) defines climate change risk as a function of three core elements: hazard, exposure and vulnerability. Hazard refers to

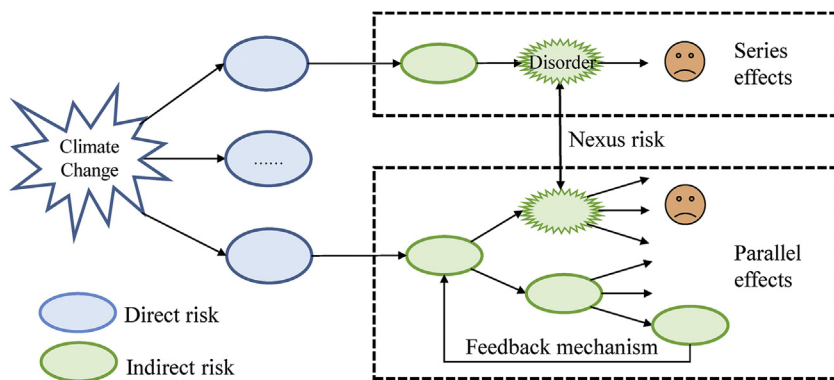


Fig. 2. The occurrence mechanisms of systemic risk.

the frequency and intensity of extreme weather and climate events. Exposure refers to the exposure of the population, infrastructures and social wealth to the risk. Vulnerability refers to the vulnerability of a system to a certain risk, as well as its ability to cope, resist and recover. The framework can also be used to understand the propagation and evolution of systemic risk (Fig. 3).

A systemic risk is connected by various discrete risks. In the process of risk propagation, the adverse consequences generated in a previous link become the disaster-causing factors in the next link. The extent and duration of risk propagation in a certain link mainly depends on the impact of the previous link and the exposure and vulnerability of this link. This link-to-link transmission leads to the spreading of systemic risks across regions and sectors.

Once a systemic risk occurs, it usually accelerates and cascades in a way that is hard to predict. Due to this characteristic, the identification and quantification of systemic risk is very challenging. Therefore, systemic risk analysis usually assumes a scenario first and then deduces the conditions for the occurrence of the scenario backward. In most cases, risk indicators depend on the origin and the causal chain of the systemic risk involved.

4. An assessment framework of systemic risk induced by climate change

Risk assessment occurs after risk identification. It is the process of collecting and analyzing data following certain methodology, estimating and measuring the probability of a risk and its impact, and determining the risk class and the level of priority for risk management.

Climate systemic risk may affect different aspects of society. Estimating the severity of the consequences based on the potential economic losses only will ignore a series of impacts that are hard to quantify. Assessment of systemic risk must take into account the diversity of the system and the integrated effects on politics, the economy, society, culture, and the environment. According to the characteristics of the climate change impacts, this paper identifies five impact domains: economy, society, homeland security, human health, and living conditions, based on which we set up a schematic assessment framework for systemic risk (Fig. 4). The framework consists of three core indicators: impact domains, severity of impact, and probability of occurrence.

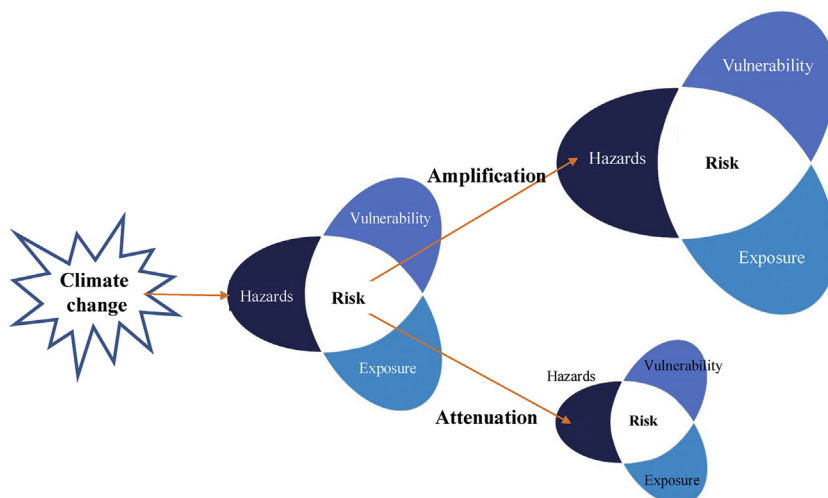


Fig. 3. The propagation and evolution of systemic risk.

4.1. Impact domains

4.1.1. Economy

The influence of climate change on economy has received extensive scholarly attention. The economic impact is usually measured by standard monetary value, which is a core indicator frequently used in risk assessments. According to the IPCC, a global temperature rise of 2 °C will lead to an economic loss of about 0.2%–2% of GDP (IPCC, 2014). This assessment result depends on a variety of assumptions, without considering extreme events and some irrevocable disasters. Carleton and Hsiang (2016) draw conclusions based on a large amount of research, that an increase in temperatures by 1 °C will affect economic production by roughly 1%–1.7%.

4.1.2. Society

Climate change may influence society through food production reduction, water resource crisis, and human health impacts, and create social crises such as mass migration of impoverished population and social conflicts. Abundant evidence has shown the linkage between climate change and these social issues (Carleton and Hsiang, 2016; Hsiang et al., 2013; Lee, 2018; Lee et al., 2019; Schug et al., 2019; Wischnath and Buhaug, 2014). For instance, Hsiang et al. (2013) analyze more than 60 empirical works and conclude that for every 1 standard deviation change in the direction of a warmer climate or some extreme precipitation, the frequency of social conflicts would increase by 4%, and the frequency of inter-organizational conflicts would increase by 14%.

4.1.3. Human health

Climate systems have a huge impact on human health by affecting human behaviors, disease vectors, and human living environment. Common assessment indicators include morbidity, mortality, and disability adjusted life year (DALY) (Carleton and Hsiang, 2016). Deschênes and Greenstone

(2011) investigate the relationship between daily temperature and annual mortality rate, and conclude that in 1968–2002 climate change increased mortality rates by 11.2%, and by the end of the century, climate change would lead to an increase of 3% in the age-adjusted mortality rate.

4.1.4. Homeland security

Homeland security is primarily about domestic prevention, protection, adapted response to major natural events, accidental, and manmade disaster risks prevention for civilians and property (O'Sullivan and Ramsay, 2015). Climate change has an important impact on homeland security through sea level rise, flood, drought, and other disasters. For example, land inundation due to sea level rise poses risks to the territorial integrity of small island states and states with extensive coastlines. The changes in shared water resources and pelagic fish stocks have the potential to increase rivalry among states. Ide et al. (2020) show that climate-related disasters increase the risk of armed conflicts in countries characterized by the political exclusion of ethnic groups, a low level of economic development and a large population.

4.1.5. Living conditions

Climate change has an impact on the sea level, water resources, ecosystem infrastructures, and other aspects, thus threatening the human living environment. For example, freshwater-related risks of climate change increase significantly with an increasing concentration of greenhouse gases. The fraction of the global population that will experience water scarcity and major river floods will increase along with warm-up of the 21st century (Field et al., 2014). McKinsey Global Institute (2020) evaluates the physical impacts of climate change from five aspects, including livability and workability, food systems, physical assets, infrastructure services, and natural capital. These factors are closely related to human living conditions. The research results show that by 2030, all 105 countries under study would likely experience an increase in at least one of the indicators.

4.2. Severity of impact

The severity of impact of systemic risk depends on the size of the risk event, the level of risk exposure, the vulnerability of the exposed population, the effectiveness of mitigation actions, and the areas affected. If the external harm interacts with the rational or irrational behaviors of individuals together with some collective response, even if the initial harm is small, the social risk may be greatly amplified. A political crisis is possible if risks occur suddenly, affecting people and society at large (CEPCC and UKCCC, 2018).

Different systemic risks have different formation speed and latent periods. Incremental risks are usually less obvious but can pose serious threats (WEF, 2020). Their long latent period leads to severe underestimation of long-term consequences. In fact, most climate risks are incremental, with impacts slowly accumulating and potentially triggering sudden, irreversible tipping points. Emergency events may trigger emergency

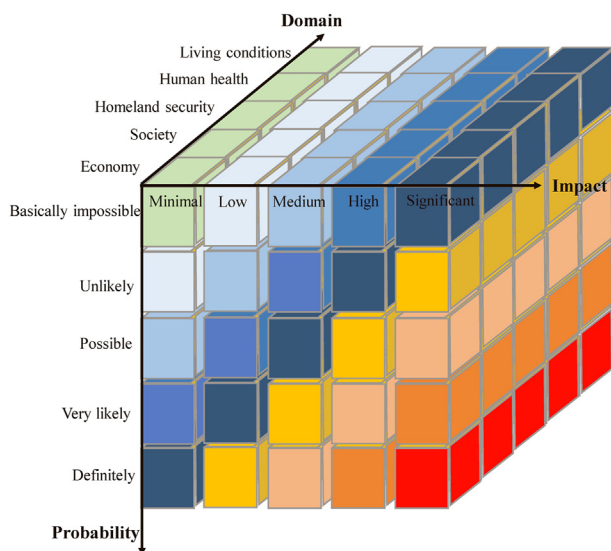


Fig. 4. Assessment framework for systemic risk.

risks, such as extreme weather disasters, which can quickly trigger extremely severe disasters under certain risk exposure and vulnerability.

Assessment of the severity calls for uniform metrics for the same domain. Generally, the economic impact can be measured by monetized economic loss, the impact of living conditions can be measured by the loss of livable land area, and the impact of health can be measured by the years of potential life lost. In contrast, the impact of society and homeland security is not easy to measure by the uniform indicator. What is more, how to rank the risks is also a challenge. Even for the same economic loss, some assessors rank it as high, while others may rank it as minimal. Therefore, it is critical to establish a set of uniform criteria for risk assessment. For facilitating the future assessment, we launched concise rank criteria (Table 1). Assessors can employ the table to rank the different climate impacts.

4.3. Probability of occurrence

Systemic risk assessment is less concerned with low probability, low impact events and high probability, low impact events. Because the former is unlikely to happen, and if it does, the impact will be small; as for the latter, due to its high probability of occurrence, the government can usually predict and manage such low-impact events very well. Systemic risk assessment focuses on high probability, high impact events and low probability, high impact events. These events are likely to be underestimated by governments because of their scarcity or their high prevention costs.

5. Typical cases of systemic risk induced by climate change

Risks do not necessarily lead to disasters, but disasters are usually transformed from risks. Some typical disaster events can help us understand systemic risks. This section presents two cases to illustrate systemic risk. The first case is about the heavy snow, sleet and freezing rain disaster that happened in South China in 2008, which reflects several characteristics of an emergency risk; the second is the risk of water shortages in

Africa, which illustrates the characteristics of an incremental risk.

5.1. Case 1: heavy snow, sleet and freezing rain disaster in 2008 in southern China

From mid-January to early February 2008, the southern part of China suffered four consecutive heavy snow, sleet and freezing rain disasters, which affected electricity, transportation, agriculture, energy, ecological system, and tourism in 20 provinces, generating serious systemic impacts (TSC, 2008). Fig. 5 summarizes the disaster' transmission routes. From the perspective of weather conditions, freezing rain against the backdrop of the La Niña event is the main cause of this disaster. Although the causes of this disaster cannot be directly attributed to climate change, climate change is an important reason for the frequent occurrence of extreme climate events (Ding et al., 2008), which provides important references for such events in the future.

According to the official statistics after the disaster (TSC, 2008), the direct effects of the event include: **1) damage of electricity facilities.** The electricity transmission lines of 13 provinces were damaged to varying degrees. Power supply in 170 counties was cut off. 2018 substations were shut down, and power supply in some areas was cut off for more than 10 days. **2) Disruption of transportation.** The Beijing–Guangzhou and Shanghai–Kunming railways were blocked due to power cuts. Nearly 20,000 km of expressway and 220,000 km of ordinary road were paralyzed. Many civil aviation airports were forced to shut down, and a large number of flights have been canceled or delayed. **3) Diminishing agricultural production.** Crop production was reduced by more than 30% than average historical level in 7.37 million hm^2 of land, of which 1.97 million hm^2 was completely barren. **4) Forest ecosystem damage.** 19 million hm^2 of forest was affected by the weather events.

These direct effects generated a series of indirect effects that spread to the broader economic sector and infiltrated into the social sector, creating a cascading effect that shows the classic characteristics of systemic risk. The indirect impacts of the event are greater than the direct impact (TSC, 2008): **1) A**

Table 1
Ranking criteria on the severity of impact for five domains.

Domain/severity	Minimal	Low	Medium	High	Significant
Economy	Property damage for some residents	Regional property damage	The lifeline system destroyed in individual cities	Disruption of major national projects	Economic stagnation
Society	The process of reducing poverty slows down	Climate poverty	Internal climate migration	Transnational climate migration	Refugees and social unrest
Homeland security	Illegal immigrants	Resource conflicts	Diplomatic interruption	Local conflicts	International geopolitical conflicts
Human health	Amplify general diseases	Malnutrition	Social life expectancy shortened	Local infectious diseases	Global infectious diseases
Living condition	Local damage within the resilience range	Regional damage within the resilience range	Living condition deterioration within the threshold range	Unrecoverable living condition deterioration	Permanent loss of livable land

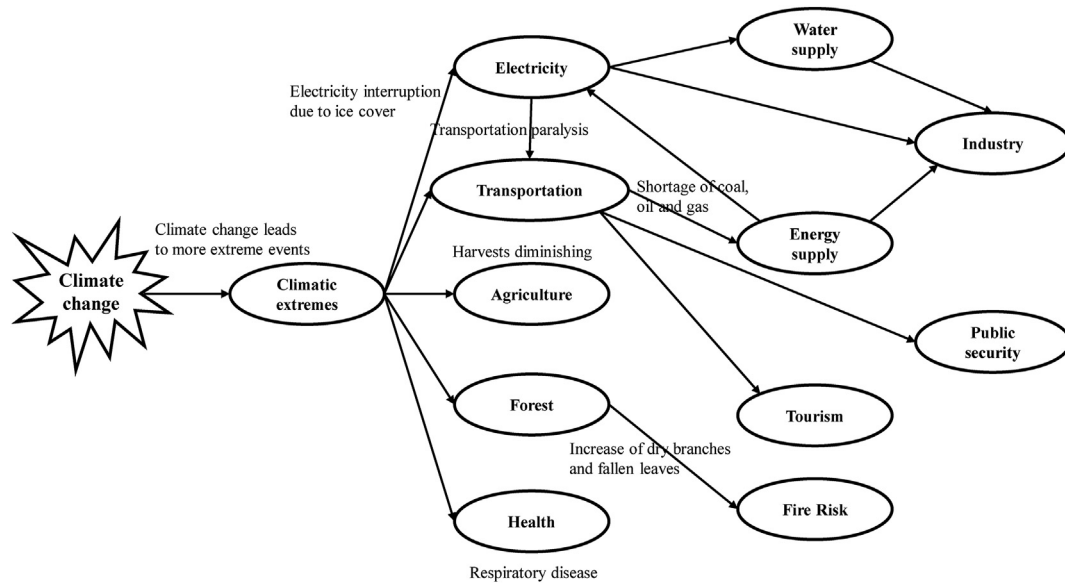


Fig. 5. The impact domains and propagation channels of the 2008 heavy snow, sleet and freezing rain disaster in southern China.

large number of industrial enterprises had to be shut down due to energy shortage. 83% of industrial enterprises in Hunan and 90% in Jiangxi stopped production for several days. **2) Livelihood of residents was seriously affected.** Water pipes in Wuhan, Jingzhou, Yichang, and other cities in Hubei province were frozen and cracked, leaving 2.8 million people without drinking water, while power outage and other incidents made water supply even more difficult. **3) Tourism was also hit hard after the event.** During the Spring Festival holidays, the number of tourists in the 19 provinces decreased by 9.7%, and the tourism revenue decreased by 11.5%. The worst-hit seven provinces, including Hunan and Guizhou, saw a 28.1% drop in the number of tourists and a 29.8% drop in tourism revenue during the same period. **4) The risk of forest fire, diseases, and pests greatly increased.** The disaster caused a large number of trees to fall, break off and die, and the accumulation of dead branches and leaves on the ground increased sharply, increasing the risk of forest fire, diseases, and pests. Compared with previous years, the surface combustible load of the affected forest increased by 2–10 times, and risk of forest fire in spring increased by one to two levels. In northern Guangdong province, the number of dry-eating pests increased significantly after the disaster, among which boring insect population increased by about 90 times in the second year after the disaster compared with the previous year. **5) Public security was affected.** The event occurred during the Spring Festival, and millions of passengers were stranded at stations, airports, and along railways and highways, including nearly 800,000 stranded passengers in Guangzhou alone, seriously endangering public security.

As an event that has already occurred, it is meaningless to analyze its probability of occurrence. Based on the ranking criteria presented in Table 1, we assess the severity of the disaster. On the whole, the impact of this event is mainly concentrated in the economic domain and has a slight effect on the domains of society, human health, and living conditions. In

the economic domain, the direct economic loss of the disaster reached 151.65 billion CNY, accounting for 0.48% of the GDP in that year. If considering the indirect losses, the ratio rises sharply. Regarding the scope of the impact, the incident involved 20 provinces, and major national projects, including the west-east power transmission channel, Beijing–Guangzhou, Shanghai–Kunming, and Beijing–Zhuhai expressway, were damaged. The assessment result of the economic impact is High.

In the domain of society, the event increased the public security risk due to a large number of stranded people. However, the disaster did not have a substantial impact on social stability. In the domain of human health, the disaster caused a total of 129 deaths. It increased the incidences of respiratory diseases, cardiovascular and cerebrovascular diseases, and intestinal diseases et al. However, the overall impact was short-term and did not substantially affect the average state of social health, and the overall rating was Minimal. In the living conditions domain, the disaster collapsed 485,000 houses, damaged 1.686 million houses, involving 1.66 million people. It caused a regional influence on the living conditions, but the damage is recoverable, and so its severity is ranked as Low.

5.2. Case 2: the risk of water shortage in Africa

Climate change has contributed to water shortage in Africa, although non-climate drivers such as population, economic growth and expansion of irrigated agriculture may have a stronger influence on future water availability (Beck and Bernauer, 2011; IPCC, 2014; Wolski et al., 2012). Fig. 6 presents a possible risk chain of water shortage in Africa.

First, water shortage may exacerbate Africa's already fragile agricultural production. Not only will climatic zones suitable for growing perennial cash crops diminish significantly, but crop productivity will also be seriously damaged, which will exacerbate food security and nutritional deficiency. In addition,

water shortage will cause excessive growth of drought-tolerant species and lead to an increase in pests and diseases. On the one hand, pests and diseases affect agricultural production and ecosystem functions. On the other hand, they may cause the wide spreading of some insect-borne diseases and have adverse effects on the prevention and control of infectious diseases.

Malnutrition, with its potential life-long impacts on health and development and its contribution to vulnerability to malaria and diarrheal diseases, can result in severe health risks. At the same time, crop failures also have a significant negative impact on household income in the region, while the decrease in income will increase the possibility of migration. Low per capita income, economic contraction, competition for scarce resources, combined with other adverse social-economic conditions, may increase the risk of violent conflicts (Field et al., 2014; Kumssa and Jones, 2010).

Based on the risk assessment framework proposed in Section 4, we briefly assess the risk of water shortage in Africa (Table 2). Overall, the climate risk induced by water shortage in Africa is at a high level, which involves all five domains of impact: economy, society, homeland security, human health, and living condition. In the living condition domain, the dry area covers approximately 41% of the African continent, the long-term continuous drought caused by rising temperature and decreasing precipitation will significantly deteriorate the residing environment in Africa. Under the influence of climate change, the regions receiving 500–600 mm rainfall per year will experience a reduction by 30%–50% in the surface drainage, which is very likely to cause further expansion of the arid area (Misra, 2014). In the economic domain, climate change is very likely to trigger significant adverse consequences. According to the World Meteorological Organization (WMO, 2020), the overall GDP of Africa would decrease by 2.25% if the global average temperature increases by 1 °C, and by 12.12% if temperature increases by 4 °C.

In the domain of human health, climate change will intensify food insecurity in Africa. From 2012 to 2018, the number of undernourished people in the drought-prone sub-Saharan region increased by 45.6% (WMO, 2020). Besides, the deterioration of living conditions and economic stagnation

Table 2

The assessment result on the risk of water shortage in Africa.

Domains	Severity of impact	Probability of occurrence
Economy	Significant	Very likely
Society	High	Possible
Homeland security	Medium	Possible
Human health	Medium	Very likely
Living condition	High	Very likely

Note: The severity of impact and probability of occurrence depends heavily on the regional risk governance. This risk assessment result is preliminary, and its objective is to illustrate the assessment framework of systemic risk.

can lead to inadequate public health care systems, insufficient access to safe sanitation, and other climate-sensitive health outcomes, such as Malaria, Leishmaniasis, Rift Valley Fever, and other diseases. In the domain of society, climate change may intensify regional migration away from areas with lower water availability and crop productivity (Mueller et al., 2020; Rigaud et al., 2018). However, human migration has social, political, demographic, economic, and environmental drivers, which may operate independently or in combination, and the role of climate change is controversial (IPCC, 2014). Therefore, we assess its probability of occurrence as Possible. In the domain of homeland security, the U.S. Department of Defense identified climate change as a “threat multiplier” and “accelerant of instability” as early as 2014 (USDOD, 2014). The degradation of natural resources will contribute to increased conflicts over the distribution of vital strategic resources (MGI, 2020). Climate change is often not the sole factor in conflict; the outbreak of armed conflict depends on many country-specific socio-political, economic, and cultural factors. Therefore, our assessment on homeland security is conservative, with a Medium impact and a probability of Possible.

6. Conclusions and future research agenda

6.1. Conclusions

This study develops a theoretical framework to delineate the origin, occurrence, propagation and evolution mechanism

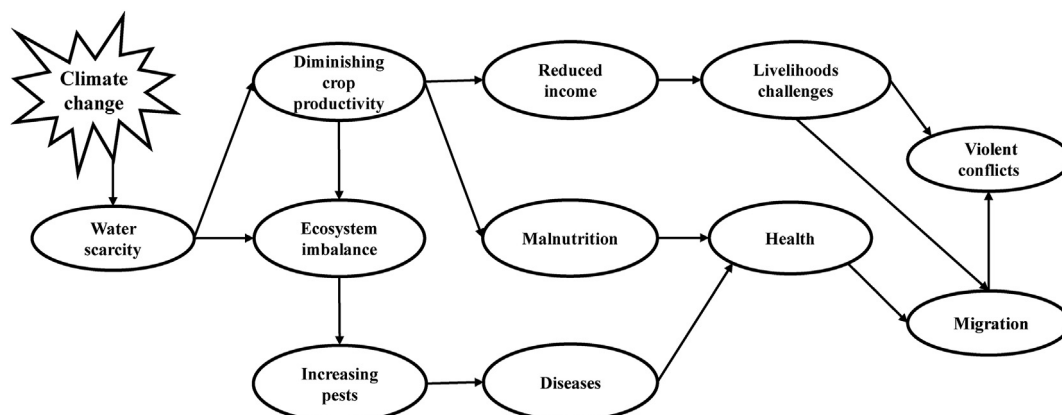


Fig. 6. Risk chain induced by water scarcity in Africa.

of systemic risk and proposes a new conceptual framework to assess systemic risk. Following conclusions are drawn.

First, systemic risk induced by climate change results from rapid growth of greenhouse emissions, increasingly complex connections among different socioeconomic systems, and continuous changes in exposure and vulnerability. The fundamental, defining feature of systemic risk is cascading effects. The extent of risk propagation and its duration depend on the characteristics of the various discrete risks that are connected to make up the systemic risk. The extent and duration of risk propagation in a certain link mainly depends on the impact of the previous link and the exposure and vulnerability of this link.

Second, assessment of systemic risk must take into account system-wide diversity and the integrated impacts of events on politics, economy, society, culture, as well as ecology. Impact domains, severity of impact, and probability of occurrences are three core indicators in systemic risk assessment. Specifically, this study identifies five impact domains: economy, society, homeland security, human health, and living conditions. The severity of impact of systemic risk depends on the size of the risk event, the level of risk exposure, the vulnerability of the exposed population, the effectiveness of mitigation actions, and the areas affected. While most climate risks are incremental, where impacts slowly accumulate and can potentially trigger sudden, irreversible tipping points, some climate risks are emergency risks caused by emergency events such as extreme weather disasters. Systemic risk assessment mainly focuses on high probability, high impact events and low probability, high impact events instead of low probability, low impact events and high probability, low impact events.

6.2. Limitations and future research agenda

This study explains the dynamics of systemic risk induced by climate change and provides a primary assessment framework, but the study is still at an infant stage of conceptual and theoretical development. There are still some technical limitations. First, the study develops the theoretical framework based on the known risks, but there is still plenty of ambiguous and unknown risks, presenting characteristics different from known risks. Second, the study strives to capture the characteristics of systemic risk, but the assessment framework still needs to be further developed. Due to the complexity of systemic risk and the limited understanding of the risk propagation paths, this study briefly analyzes the cascading effect of the systemic risk from the perspective of the influence domain. A more precise assessment depends on the knowledge of risk details.

The high complexity of systemic risk suggests that a comprehensive understanding of systematic risk needs to integrate politics, economics, culture, society, ecology, and other fields. Future research should focus on the following three aspects. The first aspect is to develop a theoretical framework based on historical disaster risks, risk theory, ecological theory, and system theory. A complete theoretical framework is helpful to grasp the fundamental laws of systemic risk. The second aspect is to carry out regional and industrial

case studies. Extensive and in-depth observations help to identify and discover more details of the system risks, as well as to understand the complex structure of systemic risks. The last aspect is to carry out risk assessment on typical regional systemic risks. The combination of theory and practice can promote continuous improvement and update of the assessment method and better support the risk response strategy.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgment

This work was supported by the Hong Kong Special Administrative Region Policy Innovation and Coordination Office (PICO) under the Strategic Public Policy Research Funding Scheme [grant number S2019.A7.007.19S]. We thank China Expert Panel on Climate Change and UK Committee on Climate Change for their invitation to participate in the project of UK–China Cooperation on Climate Change Risk Assessment. We also thank Professor Zhou Da-Di, Pan Jia-Hua, Liu Qi-Yong, Zheng Yan, Liu Xiao-Bo and the anonymous reviewers for their invaluable inputs.

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