

Review



Cite this article: Challinor AJ, Adger WN, Benton TG, Conway D, Joshi M, Frame D. 2018 Transmission of climate risks across sectors and borders. *Phil. Trans. R. Soc. A* **376**: 20170301. <http://dx.doi.org/10.1098/rsta.2017.0301>

Accepted: 19 March 2018

One contribution of 10 to a theme issue 'Advances in risk assessment for climate change adaptation policy'.

Subject Areas:

climatology

Keywords:

climate change, risk assessment, food security, water resources, migration

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Transmission of climate risks across sectors and borders

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Systemic climate risks, which result from the potential for cascading impacts through inter-related systems, pose particular challenges to risk assessment, especially when risks are transmitted across sectors and international boundaries. Most impacts of climate variability and change affect regions and jurisdictions in complex ways, and techniques for assessing this transmission of risk are still somewhat limited. Here, we begin to define new approaches to risk assessment that can account for transboundary and trans-sector risk transmission, by presenting: (i) a typology of risk transmission that distinguishes clearly the role of climate versus the role of the social and economic systems that distribute resources; (ii) a review of existing modelling, qualitative and systems-based methods of assessing risk and risk transmission; and (iii) case studies that examine risk transmission in human displacement, food, water and energy security. The case studies show that policies and institutions can attenuate risks significantly through cooperation that can be mutually beneficial to all parties. We conclude with some suggestions for assessment of complex risk transmission mechanisms: use of expert judgement; interactive scenario building;

global systems science and big data; innovative use of climate and integrated assessment models; and methods to understand societal responses to climate risk. These approaches aim to inform both research and national-level risk assessment.

This article is part of the theme issue 'Advances in risk assessment for climate change adaptation policy'.

1. Introduction

Climate change presents significant challenges to decision-making because of its global, multi-decadal and potentially catastrophic impacts that challenge standard analyses of trade-offs [1]. While there are opportunities associated with climate change (e.g. [2]), the biggest challenge to decision-making comes from the risks posed. The simplest conceptualization of climate change risk is to equate it to the likelihood of an event multiplied by its consequences. Under this view, discrete events that affect a system, whether the impacts be positive or negative, present less risk if they have a small probability of occurring. This view has a number of limitations. First, it tends to ignore high-impact, low-probability events, because these can be hard to quantify. Second, it fails to take account of perceptions of risk and probability, which play a central role in determining responses to identified risks. Assessments of risk implicitly or explicitly incorporate judgements on tolerance of risk, for example, subjective judgements on how safe is 'safe enough' [3].

A third issue with the likelihood and consequences framing of risk is its tendency to downplay risks that are relatively far off in time or space. In national assessments of climate risk, the tendency is to examine localized consequences and internalizable costs rather than global externalities. For example, decision-makers in temperate regions may not recognize the importance of risks associated with tropical coral reef degradation. Yet reefs are often viewed as global public good with intrinsic importance in terms of the natural world; and they have clear indirect linkages to welfare and well-being elsewhere [4], which may affect temperate areas through the flow of resources, people and economic dependences. In effect, decision-makers and risk calculi give lower weight to risks that occur in the future and/or are geographically remote with second-order implications. This calculus is formalized in discounting practices in cost-benefit analysis, and in national risk assessments where costs outside of a country are invisible, or incorporated only if they are known or expected to have secondary knock-on effects [5].

The precautionary principle attempts to account for the limitations of discounting practices in risk assessment by providing a moral and legal imperative to act to avoid impacts when there is some threat of harm [6]. The core of the principle is that the likelihood or even the consequences of harm need not be known precisely prior to action on risk avoidance. The UN Framework Convention on Climate Change calls for precautionary action because climate change threatens food systems, ecosystems and the prospects for sustainable development. Each of the elements of food system and ecosystem integrity, as well as sustainable development, are highly contested. Hence, as Gardiner [6] points out, the principle is widely discussed but not widely implemented in environmental policy. Adopting a precautionary approach involves comparing the cost of inaction (i.e. the estimated cost of future risks) to the cost of action. The latter is often the larger figure; that is, the costs of action are deemed too high. Implementing precaution is also argued to stifle innovation in responses.

The precautionary principle has been useful in emphasizing the importance of mitigation. Although risks are hard to forecast, especially in a world that is rapidly changing in both physical and human terms, it is nevertheless very likely that the greater the warming induced by anthropogenic emissions, the greater the likelihood of the negative impacts, from the first-order impacts on local systems, to the transboundary and trans-sector issues identified in this paper. It is clear that limiting warming through mitigation will reduce the chance of these risks.

While the precautionary principle has been used to urge action on future risks, it does not obviously deal with the neglect of risks that are remote geographically or mediated by

second-order impacts. There are so many potential pathways for risk transmission that a fully precautionary approach would probably require, by any standards, extreme mitigation. Notwithstanding the potential for a more globally just world that mitigation might contain, new approaches are, therefore, needed to assess complex risks that transcend sectors and borders. In this paper, we assess how climate risk assessment deals with issues of complexity, focusing on mechanisms of risk transmission that significantly alter which (and whose) risks are incorporated.

Techniques for assessing risk transmission in a broad way are still somewhat limited. Our primary aim here is to highlight promising methods and begin to define new approaches to risk assessment that can account for transboundary climate risk transmission and amplification of risks through competition for resources (§5). These new approaches are underpinned by the development of a new typology of risk transmission mechanisms (§2) and a review of the techniques used for assessing transmitted risks (§3). They are also informed by three risk transmission case studies (§4) that illustrate the role of policy and markets in amplifying transboundary food security risk; climatic and resource-generated risk transmission in human displacement; and cross-sectoral and transboundary risk amplification in water and energy.

2. A typology of risk transmission under changing climates

The challenges posed by the complexity of multiple causal pathways, and how they operate across space and time, present a real challenge for risk assessment. Yet without understanding the interconnected nature of systemic risks, there can be no account of their amplification or attenuation through social processes and responses and, therefore, no accurate assessment of risk. The cross-border risk transmission mechanisms identified by the UK Climate Change Risk Assessment (CCRA) 2017 [7] are shown in figure 1. Risks are evident on a range of time scales, from current weather-induced risks to longer-term changes in climate. Uncertainty in primary impacts and in subsequent societal responses means that the ultimate result of climate change risks is not predictable, as shown in figure 1. For example, there are two possible responses to long-term climate-induced global trends: if those trends give the UK a comparative advantage ('changes in trade' in the figure) then domestic food production could become unsustainable if the response of domestic policy and business is to use unsuitable land for agriculture. Equally, if those trends result in decreased productivity then there could be a reliance on imports that exceeds that envisaged by current policy. Clearly, climate and weather risks do not respect borders. Indeed, as we show later, some risks are amplified by international borders.

Systemic risks are those that cascade through inter-related systems. Systemic risk in the global financial system is perhaps the best known of these risks, particularly in the wake of the financial crisis of 2007–2009 [9]. Helbing [10] suggests that cascading systemic risks increase in their likelihood in the presence of positive feedbacks and threshold or contagion effects, emphasizing the importance of human factors such as negligence, fear, greed and revenge. Such social dynamics are most often not incorporated in risk assessment, even though they drive how systems actually react: individuals and governments (and even automated financial systems) often act in anticipation of perceived risk and react to avoid or deal with that risk in advance of consequences. This phenomenon is often conceptualized as the social amplification of risk, where external hazards interact with behaviours of individuals and collective responses to further amplify or attenuate the risks [11]. Risks can become political crises, according to Homer-Dixon *et al.* [12], if they involve sudden onset, affect a large number of people, and have significant short-term impacts.

The mechanisms of transmission of risk from one region to another include environmental processes and their teleconnections. These include pollution travelling across jurisdictions and boundaries in flows of water and in air, and fluctuating shared resources such as fisheries or transboundary water flows. However, climate risks have broader multiple direct and indirect pathways that cascade through complex social–ecological systems [13]. Hence environmental processes are only a part of the wide array of risk transmission mechanisms, which include flows of material, movement of people, and economic and trade linkages [14]. Social responses to risk

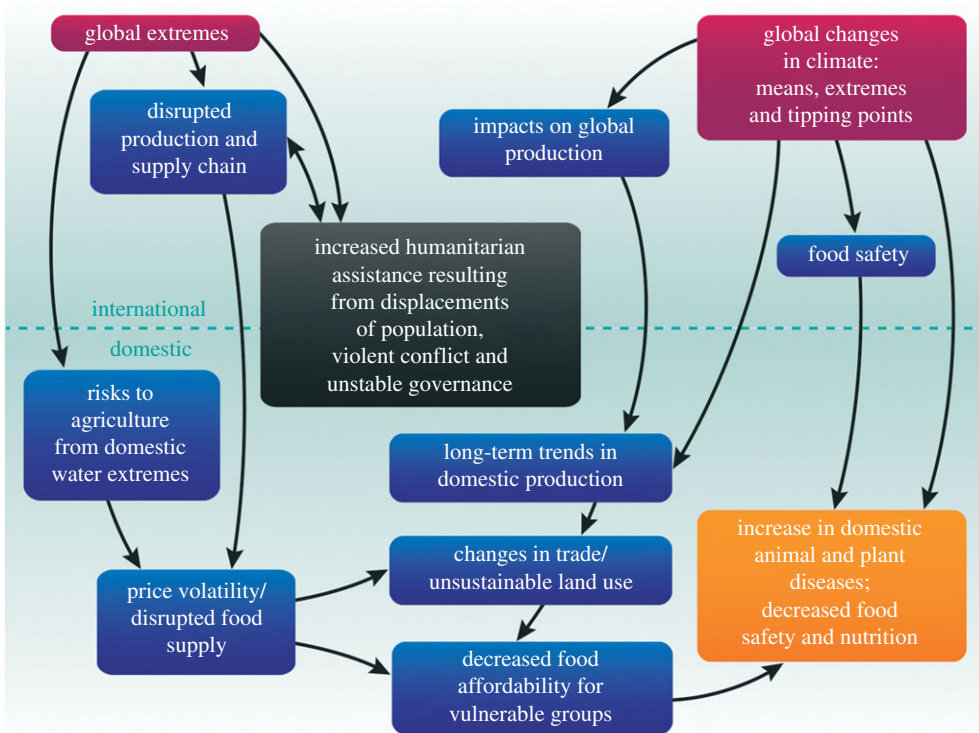


Figure 1. Transboundary risk transmission mechanisms identified in the UK Climate Change Risk Assessment 2017 [7]. See also [8]. The left-hand side of the diagram depicts current risks; these are associated with climate variability (e.g. floods that disrupt supply chains). Longer-term gradual risks are shown on the right-hand side; these are the result of changes in both the mean and variability of climate (e.g. changes in crop suitability resulting from new climates). (Online version in colour.)

come about both in reaction to exposure to risks and in anticipation of risks. Political systems, market systems, media coverage, behavioural responses and the perceptions of physical harm all interact in overall risk amplification [11,15,16]. In responding to wildfire risks, for example, land-use policies determine population densities in at-risk areas, while behavioural responses to evacuation guidelines interact in the consequences of such events [17].

We propose here a typology of risk transmission mechanisms under changing climates (termed simply ‘climatic risk transmission’) that clearly distinguishes two possible roles for climate. The first of these is as a trigger for perceived risk, a concept that builds upon the basic idea of coincident stresses as ‘long fuses’ with single triggering events leading to a ‘big bang’ [12]. This we define as climatically generated transmission, which refers to propagation via climate processes and their associated spatio-temporal properties, including across country borders and jurisdictions. Examples of this mechanism include spatial teleconnections such as the El Niño–Southern Oscillation (ENSO), which produces events with spatially coherent impacts across the world. As the climate changes, it is expected that the variability represented by ENSO will probably change, creating new emerging risks. The transmission mechanism here comes through the systematic nature of the climate risk for this type of phenomenon, which implies effects beyond the individual local climatic impacts of ENSO. Risk is transmitted because of the linked nature of climates across different regions of the world—with trends that may be relatively straightforward (e.g. warming) or difficult (e.g. extremes) to predict and detect (see §3a). Systematic spatial patterns include coherent large-scale events such as droughts that lead to multiple impacts in different countries and regions. These large-scale events may occur simultaneously (e.g. the linked Russian heatwave and Pakistan flooding of 2010; see §4a). For

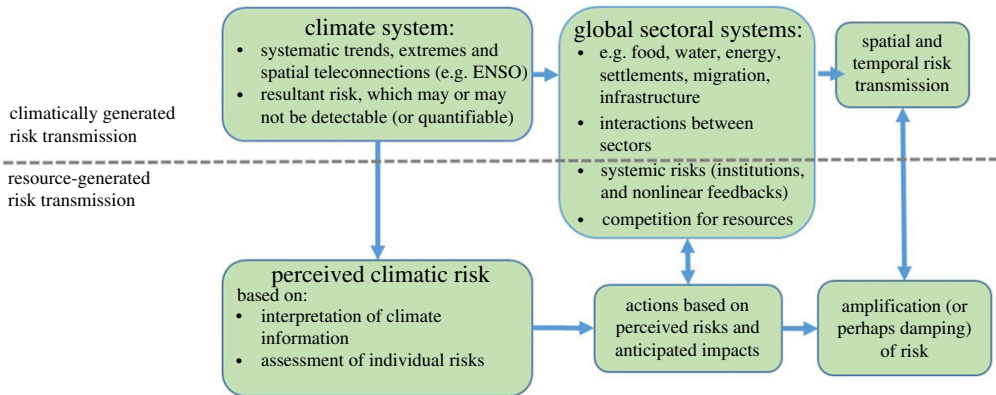


Figure 2. Pathways of resource- and climatically generated risk transmission. The former is characterized by amplification as a result of systemic risks and/or by perceptions of scarcity and risk (whether or not a real risk exists). Climatically generated risk transmission is characterized by climate-related events or processes that become more than the sum of their individual parts because of their systematic nature across time and/or space. (Online version in colour.)

these transmission mechanisms, uncertainty about the scale of impacts can be reduced through greater understanding of the biological and physical processes of risk transmission.

Our second class of climatic risk transmission mechanism is associated with real or perceived resource limitations, including where climate impacts are anticipated rather than realized. This category, which is a form of social amplification of risk, recognizes that the response to climate trends and events can often have greater consequences than the first-order climate impact itself. These transmission mechanisms typically occur across geographical scales and borders and are embedded in competition for resources and economic and political institutions. We refer to this as resource-generated transmission (usually amplification), in recognition of the fact that it is the scarcity of resource, or at least perception of its scarcity, that is the principal reason for the propagation of risk. This transmission mechanism is, therefore, characterized by amplification of risks through the social systems where those risks are ultimately manifest. Resource-generated amplification may occur because of prior systemic risk (e.g. where food systems are failing to deliver food security), or they may be dominated by the aggregate response to the climate risk, or even action anticipating real or perceived risk.

It is important to note that the typology is about risk transmission—not risk *per se*. The domain of our analysis pertains entirely to climatic risk transmission and the manner in which it plays out in various ways across the globe.

In the two classes described above, we distinguish mechanisms where climate is, and is not, the principal generation mechanism for climatic risk transmission. For any one impact there will probably be a mixture of transmission mechanisms. Figure 2 summarizes the two transmission mechanisms and their linkages. To illustrate with an example: food security in a given location is affected by the systematic teleconnections such as ENSO (upper left of figure), which disrupt economic activity and affect markets for food and other commodities (upper centre of figure). The result is a systematic pattern of impacts on food availability and/or price across multiple regions (upper right of figure). This is climatic amplification of food security risk. By contrast, the resource-generated amplification of risk is shown along the bottom of figure 2. Here, perceived risks play a key role. The various linkages between these pathways illustrate the fact that they do not act in isolation.

A key difference between the two mechanisms is that, in resource-generated transmission, climate triggers perceived risks that may or may not exist in reality; whereas in climatically generated risk transmission, climate acts as a real systematic pattern across time and/or space, which may or may not be measured, or even detectable. One mechanism is rooted in perception (social risk) and the other is rooted in the climate system.

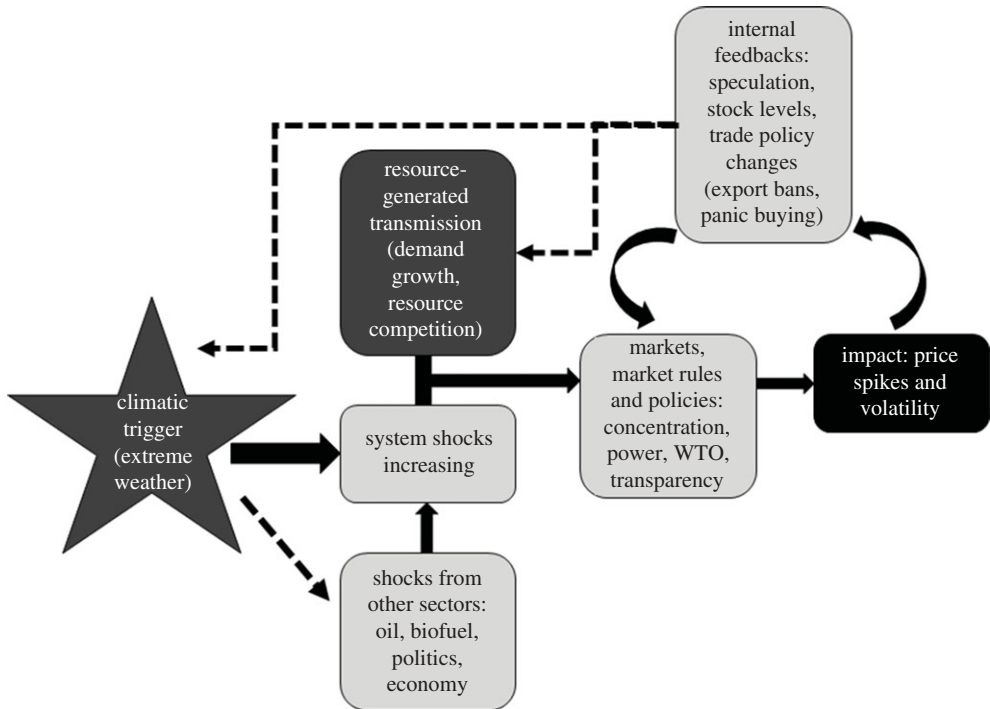


Figure 3. Resource-generated risk amplification through price transmission mechanisms in global agricultural commodity markets. Adapted from [12,18].

One impact of the transmission of climatic risks to food security is food price volatility. Figure 3 illustrates how a food system under gradually increasing pressure from demand and competition for resource is perturbed by a single climatic event. Such shocks interact with the existing market and its rules to drive price signals, which can be amplified by a range of endogenous factors. These responses can also create indirect effects reducing overall vulnerability of the system in the short term, for example, through bringing more land into agriculture (though this may increase long-term climate risk through creating more emissions of greenhouse gases). Thus it is clear that it is both the underlying properties of social systems (e.g. functioning of local markets) and the aggregate responses of social systems to underlying climate risk (e.g. international financial speculation, or export bans, affecting global markets) that can amplify resource-generated risk. In the example presented in figure 3, while the trigger is climatic, only resource-generated transmission mechanisms are in play. To the extent that climate change outpaces natural and human adaptation [19], there is however a climatically generated long-term risk transmission mechanism. Also, were the climatic trigger to be a systematic pattern such as ENSO, then that would constitute a climatically generated risk transmission mechanism. The way in which the two types of transmission mechanisms interact to play out differently in different cases is explored further in §§4a,b.

3. Current methods and tools for assessing risk transmission

There are a number of approaches to assessing risk and risk transmission. The brief and non-exhaustive review in this section informs the forward-looking content of §5. Risk can be quantified either by integration of knowledge to produce information on real-world risk, or by focusing on one component of risk (§3a). In the latter category, climate services [20] seek to tailor climate information to the specific needs of users. This is in contrast to a knowledge- and data-centric

view of climate information, which can often fail to produce actionable information [18]. Whilst such stakeholder-led approaches to risk clearly improve the utility of information [21], they cannot provide a full mapping of risk transmission. In contrast, quantified and integrated assessments of risk (§3b) provide, in theory at least, a core method for assessing risk transmission. However, in practice, assessing impacts and risk inevitably involves qualitative assessment of those components of the system that cannot be quantified [22], and so qualitative and systems approaches are required (§3c).

(a) Modelling sectoral risk using climate models

Models have long been used to quantify a diverse range of climate impacts and risks [23–25]. Inherent challenges in modelling include the choosing of appropriate prior assumptions and the associated need to explore a large range of plausible parameters in order to avoid inaccurate precision [26,27]. Even for a relatively simple quantity such as crop yield, assumptions regarding land use and water availability can systematically affect not only the absolute yields, but also the projected percentage changes [28]. Further, methods and experimental design differ across modelling studies within any one sector, making direct comparison difficult [27]. Model intercomparison studies [29] and meta-analyses [30] can be used to synthesize knowledge and improve models [31,32], thus meeting—at least to some extent—these technical challenges.

While meta-analysis of existing results can be used to summarize knowledge, continued improvement in modelling methodologies (both the models themselves and the way in which they are used) is clearly important. Recent progress includes techniques to analyse the signal of climate change relative to the ‘noise’ of uncertainty and variability in order to determine when significant impacts are expected [19,33–36]. These approaches, which identify the time of emergence of key climate signals, have the potential to directly influence policy and practice, particularly when combined with stakeholder engagement [21].

(b) Integrated and cross-sector modelling approaches

Risk transmission pathways very quickly become complex and encompass multiple sectors and spatial domains. Interactions across sectors, particularly those involving food and water, are an important determinant of climate change impacts [37]. By focusing on a subset of products, supply chain analysis provides one way of bounding the transmission system. However, it may ignore important linkages, particularly as world trade is significantly interconnected across countries and sectors. Modelling provides a means to capture greater numbers of interactions, the relative contribution from different components and system complexity, within the constraints of its underlying assumptions to simplify reality. Integrated assessment models (IAMs) aim to combine, interpret and communicate knowledge across a range of disciplines and have been widely developed and used to identify impacts associated with climate change [38]. Understanding the human activities that lead to climate change, as well as its effects on natural and human systems, requires insights from many separate disciplines simultaneously [39]. The importance of simulating interconnections is increasingly apparent, e.g. in Earth system modelling; increasing integration of sectors such as water, energy and food (e.g. the water–energy–food nexus); and combinations of multiple stressors like malaria, ecosystems, water and food security [40].

The task of integrating models presents both technical and coordination challenges. Coordinated modelling protocols are needed in order to obtain robust results [21]. These protocols can be targeted at specific questions, e.g. assessing the impacts of 1.5°C of warming [41]. They are usually developed under the umbrella of model intercomparison projects, e.g. ISI-MIP (e.g. [41]) and AgMIP [42]. Through the collaborations they foster, these international projects also help steer the direction of modelling efforts, e.g. through identifying the value of, and the challenges in, integration of new sectoral models into existing IAMs [43,44].

(c) Qualitative and systems approaches

Whilst model-based approaches can provide precise projections of the future and its risks, their accuracy, of course, depends on the modelling framework and assumptions. More qualitative approaches, while less precise, can nonetheless be indicatively useful for risk assessment, and under some circumstances can identify substantially different risks than models do, because models may have ‘blind spots’ due to an inability to capture unknown knowns (see e.g. fig. 3 of [20]). Analogues and scenarios are two qualitative approaches. Identifying analogue conditions and interpreting from them provides an observation-based way of assessing risk that can be combined with qualitative analysis of risk transmission. Analogues can be spatial (e.g. climate envelopes associated with projected climates under different scenarios; see [45]) and analogues in time (e.g. [46]). Analyses of the collapse of previous civilizations [47]—such as Angkor Wat [48] or the Mayan civilization [49]—have been conducted using these methods. Whilst such analogues never match perfectly the focal area or time (history does not repeat itself exactly), they can be instructive about the way risks are transmitted through complex socio-environmental systems.

Scenarios can inform thinking about strategic decisions, and are often useful when there are a range of key uncertainties which collectively define a set of plausible but different futures [50]. Typically scenarios are co-designed through the involvement of a range of academic and non-academic stakeholders. They do not attempt to forecast the future, but instead describe the parameter space in which the future might plausibly sit, and provide a mechanism for thinking through the challenges that might be encountered and the opportunities that might arise. Thus, scenarios can also be a tool to examine blind spots and broaden perspectives: they are less about ‘betting on a future’ and more about stress-testing plans [51,52] or beliefs to avoid over-confidence, adherence to fixed viewpoints and confirmation biases [53]. As scenarios are based on expert judgement, they are typically not probabilistic or quantitative, but they can be arbitrarily complex in ways that are difficult to model—e.g. where key mechanisms may be uncertain or unknown. They can, of course, form the basis of selecting variables and parameter values that allow modelling of pathways or projections of the future that are mathematically consistent. The scenarios used by the Intergovernmental Panel on Climate Change (IPCC) (Special Report on Emissions Scenarios (SRES) and Representative Concentration Pathways (RCPs)) are based on emissions trajectories and a narrative—the Shared Socio-economic Pathways (SSPs) [54,55]—that describe and justify their patterns.

Strategic games are a particular form of scenarios exercise that can be used for stress-testing and for risk identification and management. Here, scenarios unfold dynamically and players respond. Implicit is a feedback between the evolving scenario and the responses. A recent game [56] was used to examine the stability of global food systems under climate change. Actors represented the public sector in teams across the world, as well as international corporations. Responses to unfolding climate impacts explored how best to minimize risk propagation (especially through food price amplification) across the world.

Ultimately, country-based risk assessments are based on the range of methods and results currently in the literature. The assessments themselves also require a methodology. In UK CCRA 2017, quantitative information was supplemented by qualitative analysis. Qualitative studies that focus on interactions between risks often fill key knowledge gaps. CCRA risks were subject to an urgency scoring procedure [57], which sequentially assessed the magnitude of the risk, the extent to which it is already being managed, and the benefits of action beyond current plans within five years. While identification of risk transmission mechanisms does not explicitly form part of the methodology, they are central to the assessment of the international and transboundary dimensions of climate change within the CCRA [2]. In contrast, the third US National Climate Assessment [58] focused on climate change impacts in the USA, with risk transmission only considered explicitly via water resources shared with neighbouring countries. It has been argued that future USA assessments need to have a greater focus on risk, beginning with analysis of those decisions that are affected by climate and focusing on key risks that are relevant to the needs of decision-makers [59].

4. Illustrative risk transmission case studies

Section 2 presented a typology of risk, characterizing climatic versus resource-generated risk transmission mechanisms. There is a vast array of complex mechanisms of both types, each embedded across private actors and collective response through markets, institutions and governments. Most risks associated with climate involve both climatic and resource mechanisms (cf. figure 2). National risk assessments such as CCRA 2017 are conducted by, or at least for, policy-makers; and a key component of governance is the extent of regulation of markets. In this section, we examine a variety of observed risks that are both well documented and of significant policy concern in the light of changing climates. The focus on food security (§4a), population displacement risk (§4b) and transboundary water resources (§4c) illustrates the diverse roles of policy, markets and government responses in transmission of climatic risk. Each phenomenon demonstrates that the framing of risk outcomes determines what is measured and also affects the policy response: for food security, a focus on domestic food production—rather than food availability and price—determines policy responses. Similarly, if policy focuses on whether or not populations cross international borders, then the risk of weather-induced displacement will focus on border issues rather than social costs of displacement.

(a) Climatic and resource-generated transmission of food security risks

Whilst well-functioning markets allocate resources efficiently, there is an issue when feedbacks between markets and policy amplify price signals in nonlinear ways. It is well established that there is a complex causation between events and the volatility of global food prices, including energy policy and price, stocks, financial speculation, transparency and policy responses [12,18,60]. Whilst all of these factors interact and each one can be important (figure 3), production shortfalls generated by weather extremes are often the initial spark that drives the volatility [18]. For example, a shortfall in supply creates a price signal which markets and governments amplify by export bans that prioritize reduction of risks to local food security over global impacts. In 2010, there was one such spark: an exceptional heatwave across much of Europe, Ukraine and western Russia [61,62], which was perhaps the most extreme heatwave ever recorded [63]. The heatwave was extreme both in its magnitude, over 40°C, and its duration, from July to mid-August. At the same time, and causally related [64], the Indus Valley in Pakistan received unprecedented rainfall, creating flooding that disrupted the lives of 20 million people [65]. Analysis of hemispheric climate processes suggests that the co-occurrence of these events was related to Arctic warming and its impacts on atmospheric Rossby waves [66]. Thus there is a climatically generated component (systematic spatial pattern) to the transmission of risk operating alongside the resource-generated component (responses to perceived risk amplify risk).

The shortfall in grain harvest in Russia resulting from the heatwave amounted to about a third [67]. As it became clear that the volume of Russian grain was significantly less than expected, Russia instituted an export ban on grain, against the worry of its own internal food security. This stayed in place from August 2010 to July 2011. This shortfall in global grain production, coupled with the export ban, fuelled price rises on the global commodity markets [68]—which rose partly through ‘panic buying’ and partly through speculation [69]. As a result, the FAO cereal price index rose rapidly from a value of around 150 in summer 2010 to around 250 in spring 2011. As with 2007–2008, other countries responded in a largely uncoordinated way, each driven by internal political dynamics and national self-interests [70]. Market and policy responses can create spill-over between crops that are affected by the original weather event (wheat) and those unaffected (e.g. rice)—as was very prevalent in the 2007–2008 food price spike [71].

Analysis of responses to food price rises in 2010–2011 in Bangladesh, Indonesia, Kenya and Zambia showed that populations who are food-insecure due to low income (a) worked harder, (b) ate less, (c) lived more austere, (d) drew on savings and household assets, and (e) responded politically through criticism of their governments. Those affected perceived their problems as having a political cause, often associated with collusion between powerful incumbent interests

(of politicians and big business) and disregard for the poor [72]. This politicized response contributed to food-related civil unrest in a number of countries in 2010–2011 [73]. In Pakistan, where there were food-related riots in 2010 [73], food price rises were exacerbated by the floods, which directly affected cotton, rice, wheat and sugar, and resulted in damage and losses of US\$ 5 billion and zero growth in the sector [74].

In the UK, the upturn in commodity markets influenced food inflation, with approximately a five-fold increase in food inflation in the latter half of 2010 [75]. Analysis of purchases in the 5 years from 2007 to 2011 [76] in the UK indicated that people bought 4.2% less food, but paid 12% more for it. The poorest 10% spent 17% more in 2011 than in 2007. There is evidence that poor populations, for whom food represents a high proportion of household expenditure, also traded down to save money by buying cheaper alternatives. However, in extremis, people simply could not afford food. Use of emergency foodbanks increased nearly 50% in 2010 [77]. The fact that global markets determine local prices highlights the importance of managing the balance of risks between local people and people far away. A key cause of food price spikes comes from governments reducing local risks (by instituting export bans to hedge against supply shortfalls), at the expense of accelerating the global perceptions of likely shortfall, and global impacts.

Clearly, the issue of food security and response to climate affects all countries and parts of the global food system, while the risks are manifest in different ways in food exporting countries, countries with large poor populations, and countries that are concerned with food in terms of price and affordability. Assessment of international dimensions of climate risk for the UK, for example, highlights (in addition to opportunities, which are out of scope here) risks from extreme weather abroad impacting supply chains and prices. However, risks arise not just from extremes, but also from trends (see figure 1). Risks generated by climatic trends can be subtle and hence difficult to identify. For example, time of emergence techniques (§3a) have been used to identify a climatically generated risk transmission pathway: the mechanisms for delivering new seed (development, breeding, dissemination, adoption) fail to keep up with rates of warming, simply because the variety is bred in a cooler environment than that in which it is eventually used [19]. In both of these cases—risks to food prices and the risk of mis-matched crops—coordination of policies for risk management is a huge task involving many government departments and probably also the private sector; as well as requiring significant international coordination [2,19].

(b) Climatic and resource-generated amplification in risks of population displacement

As discussed in §4a, climate risks are manifest directly or indirectly through interactions with resources, and these risks can be amplified or attenuated through the complex interactions of markets, land use and ecological processes. The confluence of factors and the weakest link in systems can be a critical determinant of outcomes. Thus the ability to specify the contribution of climatic risk (real or perceived) can be more important in assessing likely future risks (as climate continues to change) than it is in responding to current risks.

Population displacement is defined as the involuntary and unplanned movement of people from their place of residence due to weather-related impacts on property and infrastructure [78]. Such movement is most often temporary and short-lived. But it is often highly disruptive and traumatic to those involved: Munro *et al.* [79], for example, show that displacement from flooding events in England decreased mental health and increased depression and anxiety a year after populations were evacuated from their homes. Displacement from floods, droughts and wildfire is common in every region of the world. Estimates of the number of people affected, including those directly displaced from their residences by weather-related extremes, are over 26 million per year [80].

While most people directly displaced by weather-related extreme events return to their original place of residence, such events also trigger longer-term permanent migration. The overall population of New Orleans city, for example, declined sharply after Hurricane Katrina in 2005, from 480 000 in 2000 to 344 000 in 2010, with many displaced residents not returning in a process termed staged migration [81]. The major floods in Pakistan in 2010 led to an estimated 1.6 million

damaged or destroyed homes, and responses included both quick return and more permanent relocation within Pakistan [82].

The risks associated with displacement are principally to those directly affected, through economic shocks, and the impact on public and health service provision. There is some evidence that natural disasters undermine government legitimacy directly, and/or indirectly through economic shocks, and hence increase risks of insecurity and even conflict [83,84]. But the risks to political systems are malleable and determined by how they respond. In the case of the Pakistan floods, for example, Fair *et al.* [85] showed how positive government responses and self-help collective action during the floods was perceived as positive and led to flooded populations increasing their civic and political engagement in the recovery period.

Both the Pakistan floods and the displacement in Louisiana and New Orleans associated with Hurricane Katrina demonstrate how climatic risks can be amplified through individual and collective responses. The amplification of risks occurs through both prior decisions concerning land use and uneven distribution of resources and vulnerability among populations. Responses to perceived risks can also amplify risks, even where direct impacts are, as in the Pakistan and US cases, largely contained within the borders of one country. Thus, in the language of our typology, risk of displacement and migration can clearly be the result of climatically generated transmission: large-scale droughts, floods or hurricanes can trigger displacement across borders (the weather abroad affects domestic risk directly). There is probably also a resource-generated transmission mechanism: people are displaced because they lack water, food or shelter.

Some mass displacement events are more ambiguous in terms of climatic and resource mechanisms. Displacement from drought in Syria in the late 2000s, for example, is instructive of how the question of attribution of displacement to climatic or resource-generated transmission mechanisms is less relevant than the interaction of multiple elements of risk. In Syria in that period, there is uncertainty about the scale of drought-induced displacement of populations from rural areas into cities in northern regions of the country. But the civil conflict starting in 2011 led to mass displacement of close to five million people from Syria into neighbouring countries and across the world (with 10% of the refugees moving to Europe). The first of these displacements has been claimed to be climatically triggered, while the second has been claimed to be a link between climate change and conflict [86].

Several studies have claimed a link between observed climatic changes in the northern Mediterranean region and the drought experienced by Syria and neighbouring countries from 2006 to 2009 [87,88]. The evidence falls short of risk assessment, however, because that would require identification of mechanisms and evidence of how displacement or conflict risks were amplified or attenuated following the drought. Many commentators [86] have taken the presence of the drought and the role of climatic changes in that drought as evidence of climate change playing a contributory factor both in the Syrian civil conflict and even in the European refugee crisis that resulted directly from the conflict. However, the transmission mechanisms between the weather-related risk, the resource base and the subsequent risks are, in the Syrian case, largely absent. Selby *et al.* [86] examine, for the first time in detail, whether or not the drought caused mass displacement from rural northern Syria (estimates range from 30 000 up to 1.5 million), and whether the presence of such populations in cities was involved in the conflict as participants or victims. They find a lack of evidence for either of the mechanisms. Despite this, there are significant reasons for concern that climatic changes do indeed increase conflict risk by affecting the underlying risk factors such as poverty and insecurity and the ability of states to meet expectations of their social contract to their citizens [89,90].

There are multiple examples and multiple lines of evidence that displacement of populations represents a significant risk from climate change impacts. The triggers for such unplanned displacement include [91,92] flooding, drought and long-term changes as areas become less habitable as a result of such risks and due to sea-level rise [93]. Neumann *et al.* [91], for example, show how projected population growth in urban settlements in Africa, in particular, significantly increases populations exposed to flood risk. The potential for resource-generated amplification is significant for these types of risks. Hence risk assessment, in explaining the mechanisms of

amplification, has the potential to foster policy responses that attenuate rather than amplify existing risks.

(c) Cross-sectoral and transboundary risk amplification in water and energy

Linkages between sectors can be a critical part of risk transmission (cf. upper middle box in figure 2). Similarly, the existence of shared resources across national boundaries can transmit climatic risk. Once again, both climatic and resource-generated transmission mechanisms are important, as we illustrate here for the water and energy sectors.

Freshwater use has strong spatial dimensions that act as a resource amplification of climate risks associated with trends and variability in quantity and quality. Climate processes such as the ENSO act across multiple spatial scales, and many river basins and groundwater aquifers lie across national and administrative jurisdictions. The third national US climate impacts assessment [94] identifies cross-boundary coordination at multiple levels as a requisite for ensuring that the US Great Lakes, the Columbia River and the Colorado River can deal with drought. Conversely, lack of cooperation over international waters may contribute to conflict, making the goal of cooperation important in securing regional peace [95]. In addition, there are significant amounts of water embedded in traded products, particularly food, that generate further linkages and pathways for risk transmission [96]. Globally 11% of groundwater use for irrigation comes from non-renewable resources, with depletion being greatest in those countries providing the largest source of staple crops; this water is, therefore, embedded in food trade [97].

Local patterns of water misuse or scarcity have the potential to spill over into larger domains should transboundary governance mechanisms fail. In spite of these large-scale linkages, governance of water resources is predominantly focused on water quality and quantity within watersheds and within jurisdictions. Where there is a focus on the large scale, it is often on transboundary surface waters (not groundwater) and gives limited attention to temporal variability and pollution [98]. Clearly, managing the hydrological cycle is a key component of transboundary governance. Increasing water scarcity and resulting competition for water driven by growth in population and consumption, particularly for irrigation, have been key in generating concern about global water security through resource-generated transmission of risk. Pathways of transition in societal water use include moving from exploitation to greater focus on supply augmentation and conservation [99]. In some countries with limited *per capita* water resources, particularly in the Middle East and North Africa, growing demand for food has been met through imports (with associated embedded water) [100], leading to exposure to price volatility and concern about national sufficiency.

Transboundary issues do not solely arise from degrading groundwater resources. Evaporation from land and water surfaces generates atmospheric water vapour, and recent advances in hydrometeorology have revealed atmospheric rivers or precipitation sheds, thus allowing tentative quantification of sources and sinks of precipitation [101]. Modifications to land use may alter evaporation differentially across locations, countries and even continents. Improved understanding of these spatial linkages is generating interest in the design of legal and institutional processes for the governance of moisture recycling [101].

Southern Africa exemplifies strong regional-scale connections between climate, water and energy [102]. Periodic El Niño events tend to be associated with below normal rainfall in extensive areas of the region [103,104]. The major El Niño event in 2015–2016 brought enhanced rainfall variability globally [105]—but well below normal rainfall in much of southern Africa [106]. Impact transmission pathways are enhanced by the 15 shared river basins that dominate the hydrology of the region, including the Zambezi basin, shared by eight countries. The surface basins are underlain by an estimated 16 transboundary aquifers [107]. Large-scale dams and inter-basin, often transboundary, water transfers reinforce transmission pathways. Regional governance mechanisms further strengthen the physical linkages between countries, particularly through the Southern Africa Development Community, which has established protocols on shared water, energy and food security, and initiatives on trade.

Energy security also has an important transboundary dimension through the Southern African Power Pool (SAPP), which is a regional mechanism of energy trading and infrastructure interconnections between many of the region's countries. Hydropower comprises a major component of regional energy production, accounting for over 90% of electricity generation in the Democratic Republic of Congo, Malawi, Mozambique, Namibia and Zambia [108]. Reliable electricity production is, therefore, at risk during droughts. Recent conditions during the El Niño of 2015–2016 highlight the scale of hydropower disruption associated with drought. Malawi, Tanzania, Zambia and Zimbabwe all experienced electricity outages (load shedding) partly due to the effects of low rainfall on reservoir levels and electricity generating capacity [109]. Load shedding brings significant economic disruption; for example, in May 2015 Zambia's national power utility warned that it may cut power supplies by one-third and the Finance Minister reduced the forecast for national GDP growth by over 1%, partly in response to this warning [110]. The SAPP serves in part to manage energy deficits and fluctuations through trade in electricity and may become an important dimension of risk mitigation of climatically induced supply disruption. However, intra-regional trade in energy is very low at present, and the system faces considerable political and infrastructural challenges. The systematic impact of climate on the energy sector constitutes a climatically generated risk transmission mechanism. Short-term responses in Tanzania have included use of expensive privately owned gas generators. Longer-term goals to diversify energy mix, in some cases increasing reliance on fossil fuels and exposure to price volatility, are associated with resource-generated amplification of risk (e.g. in Malawi and Tanzania).

5. Assessing systemic risk across borders and sectors: towards new methods

The challenges of incorporating climatic and resource-generated amplification as well as transboundary and trans-sector risk transmission mechanisms into national climate assessments are significant. As illustrated in §4, mechanisms range from individual climatic events to more subtle climate trends, which can interact with each other and have complex cascading ramifications on socially complex resource interactions. Climate risk assessments that are restricted to a single region or jurisdiction will find it very difficult to capture this range of mechanisms. The tools and case studies analysed above point towards a number of overlapping and complementary approaches to meeting this challenge.

(a) Plurality of approaches supported by expert judgement and interactive scenario-building

Assessment of systemic risk is likely to be very different in character from single-sector risk assessments. In particular, high-impact, low-probability events have insufficient precedents to fully understand risk transmission. The lack of sufficient precedents poses a real problem for probabilistic forecasting, where there is a direct relationship between the value of a forecast and perception of the benefits of acting on such predictions [111]. Furthermore, lack of data means that causal pathways cannot be well described, at least not without considerable uncertainty, in a model-based framework. And those pathways that are known, and well characterized, may have their impacts amplified or mitigated by less-known pathways that are not modelled. Thus whilst high-impact, low-probability events occur within single sectors, they directly affect systemic risk; and their very nature presents problems for assessing risk transmission.

Given that no single risk assessment method can be comprehensive, our recommendation is that multiple approaches are needed: quantitative, qualitative and hypothetical. The particular combination depends upon the specific domain of the system under consideration—i.e. the system boundary [21]. Examining local risks will probably require a different framework than a study of cascading global risks with indirect impact. Once the domain of a study is clear, targeted mixed-method approaches to risk assessment can be developed. These are likely to need a number

of characteristics. First, the combination of methods needs to be able to incorporate plausible, but often unknown, risks and transmission mechanisms alongside better characterized ones. This is important because indirect pathways can very often exert a much larger influence than direct pathways in complex systems, which can be highly nonlinear in nature [112,113]. The importance of understanding complex topologies for assessing systemic risks is increasingly recognized in human systems [12,114].

A second characteristic of systemic risk assessments is the ability to successfully synthesize the range of expert judgements. Lessons learnt from the IPCC Fifth Assessment Report (AR5) [89,115] on this subject include the need for a simple and rigorous framework with practices that minimize biases in expert judgement while integrating subjective expert views with quantitative evidence [116]. One area where such integration is very important is that of low-probability, high-impact events such as flooding, where the limitations of modelling imply a need for new methods that use models in targeted ways alongside expert judgement.

Scenario-based approaches (§3c) may prove effective in integrating the views of a range of stakeholders with the methods and results from theoretical approaches to risk assessment. They can be used to examine the consequences of plausible futures, and test whether the current state of the system would be able to cope with them, or how shocks may play out within them. They can also be useful to design policy (public or private) that may work to minimize risks or costs and maximize benefits. For example, in a future where the world is more regionalized and less globalized [55,115], it might be expected that a focal country would be less exposed to climate shocks elsewhere in the world, but more exposed to local effects. In such cases, what policy (such as local stocks of food) could buffer against shortfalls? Similarly, different plausible scenarios may differentially represent costs and benefits, and backcasting from the more desired futures [117] can create pathways, or timelines, that represent decision points, opportunities and threats. Participatory scenarios and backcasting also act to create common understanding and ownership of risks and opportunities.

While scenarios are typically qualitative pathways having a narrative nature, more sophisticated analyses can be conducted that involve quantitative analysis. For example, the IPCC scenarios involve both a narrative strand and model-based analysis of pathways. Furthermore, expert, qualitative, analysis of scenarios or sensitivity analyses of models can indicate where there may be particularly strong leverage points—where small changes may exert large influences—and, therefore, be the focus of policy development.

The processes through which decisions are made in conditions of uncertainty is highly relevant to risk transmission, both because the transmission mechanisms themselves involve decisions (see §§4a,b) and because existing methods for planning under deep uncertainty, e.g. dynamic adaptive policy pathways [118], might be tailored to deal with transboundary systemic risk (see §4c). Existing approaches that allow for the diverse views of stakeholders in generating robust plans [119] could prove useful, given that perceptions of risk differ, and precision in quantifying transboundary risks is often not possible. Pathways and backcasting approaches will no doubt prove useful in assessing system risk across borders and sectors. Promising areas include mapping out path dependences and foster adaptive policy-making [118]; and assessment of the implications of path dependence, interactions between adaptation plans, vested interests and global change [120].

(b) Global systems science and big data

One clear message from the research reviewed in this paper is the criticality of understanding systemic risk; it is the landscape in which risk transmission occurs and goes well beyond the kind of risks usually associated with climate change. There is widespread recognition of the potential for cascading failures in trade, financial, infrastructure, health and environmental systems, and the role of climate change in initiating cascades. Separate disciplines are promoting their insights to the study and management of these challenges whilst recognizing the need for new multi- and inter-disciplinary approaches. These new complex interconnected systems are fundamentally

different and at present our understanding is limited to individual, sparse or static networks [10]. Walker *et al.* [121] see gaps in the functions that existing transnational institutions provide to address global-scale failures and argue for improved design of institutions with stronger focus on cooperation, willingness to implement agreements and the need for legitimacy. Helbing [10] proposes a ‘global systems science’ to meet the required knowledge demands. Design and operation principles in the application of this science include: the use of self-organizing systems with the aim of achieving resilient system design and management; the need for back-up systems running in parallel to any primary system; that diversity can promote systemic resilience, adaptability and innovation; that system size should be limited; and that reducing connectivity to reduce the strength of interlinkages should be considered. In particular, new combinations of risk can be assessed using network analysis, the use and collection of big data, and innovative machine learning techniques to analyse and make use of new insights into emergent patterns of behaviour [10].

The internet and social media now provide vast scope for data and news (and, unfortunately, misinformation) about disease outbreaks, economic indicators and other events through press reports, blogs, chat rooms web search analytics, Google Trends and tweets [122,123]. Citizen science has an important role to play in this emergent arena, with its potential to act as a powerful self-organizing force. Areas for further research and development include understanding of the quantity and quality of information, methods for guaranteeing the trustworthiness and security of information, ways to integrate formal and informal sources of information, and new ways for extracting information [124].

Complex systems and ‘big data’ approaches are not a panacea—social science highlights the importance of the societal dimensions that include, among other things, reputation, trust, social norms, culture and behaviour [10,125]. Indeed Galaz *et al.* [125] argue there is often failure to integrate insights from the wider social sciences in relation to globally networked or systemic risks leading to naive assumptions about the behaviour of government and non-governmental actors in the real world. They identify five key conditional insights from diverse literature as follows: while international institutions are important, they are challenged by globally networked risks; while the international norms evolve slowly, they can in some instances respond rapidly; while institutions for international crisis management are critical, they are difficult to reform (even after crisis); while stimulating new capacities is important, successful policy initiatives are often difficult to up-scale; and while there is a strong relationship between legitimacy and effectiveness, it is often unclear what the best reform options are [125]. In this vein, Centeno *et al.* [126] highlight how social problems are constructed and how responses reflect social hierarchies. They stress there is endogeneity of risk within global systems; that the actual structure and processes followed by organizations to manage local risks may ultimately produce larger systemic risks [126]. They find value from the deep insights, arising from fine-grained analyses of qualitative research on specific contexts, about elements of complexity, how they arise and how they interact.

(c) Innovative use of climate and integrated assessment models

Climate models can be more than sources of input data for impacts and assessment models. The re-framing of uncertainty into the time dimension—i.e. the ability to ask when climate signals are likely to emerge from the background noise of climate variability [35,36], i.e. the ‘time of emergence’ (ToE)—has the potential to make a significant impact on methods for assessment of systemic risk, including transboundary issues outlined in §4c. ToE can be calculated for first-order variables that are fundamentally important to cross-border risk transmission—as in the case of crop breeding reviewed briefly in §4a. Systematic trends in extreme events are more difficult to detect [33] and may require long climate model simulations with constant forcing, and analysis of long-term observations, in order to properly estimate probabilities.

The spread in responses of physical models to climate change makes quantification of ToE for some variables such as precipitation difficult. However, some of the variables identified above as

being important for cross-border risk transmission, such as aridity and basin-scale river flow, are driven by changes in both temperature and precipitation, making estimates of ToE more tractable [127]. Furthermore, impacts such as sea-level rise and cryospheric changes are functions of time-integrated radiative forcing or integrated temperature responses, which also implies tractability. Others, such as ecosystem changes that depend on the ‘velocity of climate change’ [128], may be represented by rates of change of the atmospheric circulation.

There are several ways in which models in the natural and social sciences can be used to estimate systemic risks in the sort of multivariate, transboundary cases considered in this paper. Here we briefly consider two. The first is tractable, practical and quantifiable: use models of the climate system and single-sector impact models (see §3a). While cross-sectoral interactions or complex value chains will not be captured, this approach could identify the primary sites from which significant, early transboundary risks might emerge, with such groups of countries being identified as ‘earliest common denominators’ [35]—those most likely to emerge as the earliest candidates for specific vulnerabilities.

In contrast to the model-centric scanning of the globe implied by the earliest common denominators approach, a second, more qualitative, approach focuses on potentially cascading impacts—an important property where resilience is determined by the chance of surprises. Many transboundary risks are shaped by multi-sectoral factors, and the role of IAMs in resolving these has been detailed in §3b. A key challenge here is to focus on how complete multi-sectoral analyses are, given uncertainties in the baseline case: cross-sectoral sensitivities might significantly change as the world warms and circulation, precipitation and aridity patterns are altered. Similarly, the physical teleconnections that are now known from climatology might themselves change, implying very different cross-sectoral and geographical sensitivities. IAM-based approaches must, therefore, undertake the difficult task of attempting to understand, quantitatively or qualitatively, the possibility of dramatic or even radical changes to patterns of production, trade and cross-sector dependences. Here the idea of ‘earliest potential pinch points’—those pathways most likely to emerge as earliest candidates for disruption—may prove useful for thinking about how such complex system-wide multi-sectoral pathways might be represented, and also for how IAMs might be evaluated.

(d) New approaches to understanding and supporting societal responses to climatic risk

Climate risk assessment usually focuses on direct mechanisms of transmitting risk, and the societal response is often either omitted completely or limited to the role of markets. New approaches are needed to understand societal roles, both within and well beyond markets. Well-functioning markets can allocate resources in response to climatic risk: if there is a shortfall in supply, price signals increase supply. However, there is an issue when markets and policy amplify the price signal in a highly nonlinear way (see §4a). Markets work within the framework of national and international policy, both of which have typically had their focus on economic growth and the global public good that comes from lowering prices. We suggest that a greater understanding of risk management and amplification will enable new thinking on how markets can best serve society. How can markets function to deliver public goods (low prices and economic growth) on average, as well as in a way that is robust to the complex risks arising from climate change? What are the properties of a market that attenuate rather than amplify risk?

A second area where improved understanding of societal roles would support risk attenuation is that of decision-making. Section 5a emphasizes the role of plurality in improving understanding of risk transmission and building scenarios. While this includes societal roles, the gap in understanding is sufficiently wide that a specific focus on these roles is well justified. There is a literature on decision-making under uncertainty that, while not yet dealing explicitly with transmission of climatic risk across sectors and borders, is likely to be highly relevant to new methods of assessing systemic risk in those settings. For example, structured yet flexible approaches for assessing causal risks within and across food, energy, environment and water systems already exist [129].

A focus on decision-making within the risk transmission typology presented here may come to yield direct benefits to risk assessments. The centrality of perceptions of risk in the resource-generated mechanism suggests a key role for climate information in aligning perceptions with reality. Analysis of climate and other data (§§5a–5c) may yield additional benefits by identifying unforeseen risks (as in the crop breeding case in §4a). Equally, the systemic nature of climate suggests the potential for coordinated, or at least synergistic, decision-making—as outlined in our discussion of markets and policy.

6. Conclusion

In this study, we have examined the challenge for risk assessment posed by climatic risk transmission cascades over space and time. Food security, population displacement and the management of transboundary water resources are key risks with important transboundary and trans-sector dimension. Their dynamics differ, and they also interact. Our analysis shows that policies and institutions can attenuate risks significantly through cooperation that can be mutually beneficial to all parties. Assessing risk transmission mechanisms across sectors and international boundaries, and coordinating policies across government departments and across local and national governments, are, therefore, necessary steps in prioritizing adaptations to changing climates [8]. Assessments and policy approaches of this kind can only be achieved through broad framings of risk. One such framing, used throughout this study, focuses on the role of climate versus that of societal responses and perceptions; i.e. climatic and resource-generated amplification mechanisms. Other framings, developed in §5, focus more on the development of new methods for this complex challenge. We hope that these framings can support future national-level risk assessments, ensuring that they take adequate account of climatic risk transmission mechanisms.

Data accessibility. This article has no additional data.

Authors' contributions. A.J.C. led and compiled the analyses, based on intellectual input and concepts discussed and proposed by all authors and refined among all authors. All authors contributed to the writing of the manuscript.

Competing interests. We have no competing interests.

Funding. W.N.A. and A.J.C. acknowledge support from the UK Department for Environment, Food and Rural Affairs in the preparation of the International Dimensions Assessment of the UK Climate Change Risk Assessment. W.N.A. acknowledges support from the High-end Climate Impacts and Extremes project of the EU. A.J.C. acknowledges support from the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). D.C. acknowledges support from the UK Economic and Social Research Council (ES/K006576/1) for the Centre for Climate Change Economics and Policy (CCCEP).

Acknowledgements. We thank Matthew Baylis, Duncan Depledge, Andrew Geddes, Steve McCorriston, Manuela DiMauro, Kathryn Brown, Daniel Johns and Lindsay Stringer for initial collaboration on the International Dimensions Assessment of the UK Climate Change Risk Assessment as the basis for this paper.

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