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Transmission of climate risks across sectors and borders

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Summary

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 co-operation that can be mutually beneficial to all parties. We conclude with some suggestions for assessment of complex risk transmission mechanisms: use of expert judgment; 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.

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]. Whilst there are opportunities associated with climate change [e.g. 2], the biggest challenge to decision-making comes from the risks posed. The simplest conceptualisation 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, since 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 judgments 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 localised consequences and internalisable costs rather than global externalities. For example, decision makers in temperate regions may not recognise 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 dependencies. 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 formalised 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; i.e. 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 emphasising 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.

Whilst 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 likely 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, focussing 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 (section 5). These new approaches are underpinned by the development of a new typology of risk transmission mechanisms (section 2) and a review of the techniques used for assessing transmitted risks (section 3). They are also informed by three risk transmission case studies (section 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 2017 [7] are shown in Fig. 1. Risks are evident on a range of timescales, 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 Fig. 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.

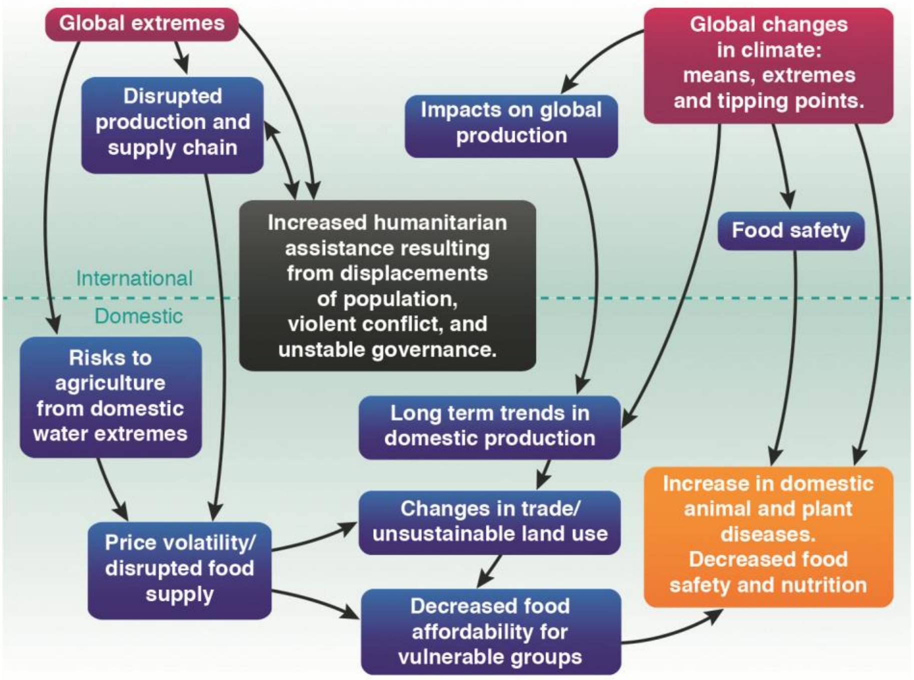

Figure 1. Transboundary risk transmission mechanisms identified in the UK Climate Change Risk Assessment 2017[7]. See also [8]. The left-hand side of the diagram depicts current risks; these are associated with climate variability (e.g. floods that disrupt supply chains). Longer term gradual risks are 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).

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 conceptualised 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 and colleagues [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 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 section 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 heat wave and Pakistan flooding of 2010; see section 4). For 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 realised. This category, which is a form of social amplification of risk, recognises 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 characterised 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 likely be a mixture of transmission mechanisms. Fig. 2 summaries 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 affects 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. In contrast, the resource-generated amplification of risk is shown along the bottom of the figure. Here, perceived risks play a key role. The various linkages between these pathways illustrates the fact that they do not act in isolation.

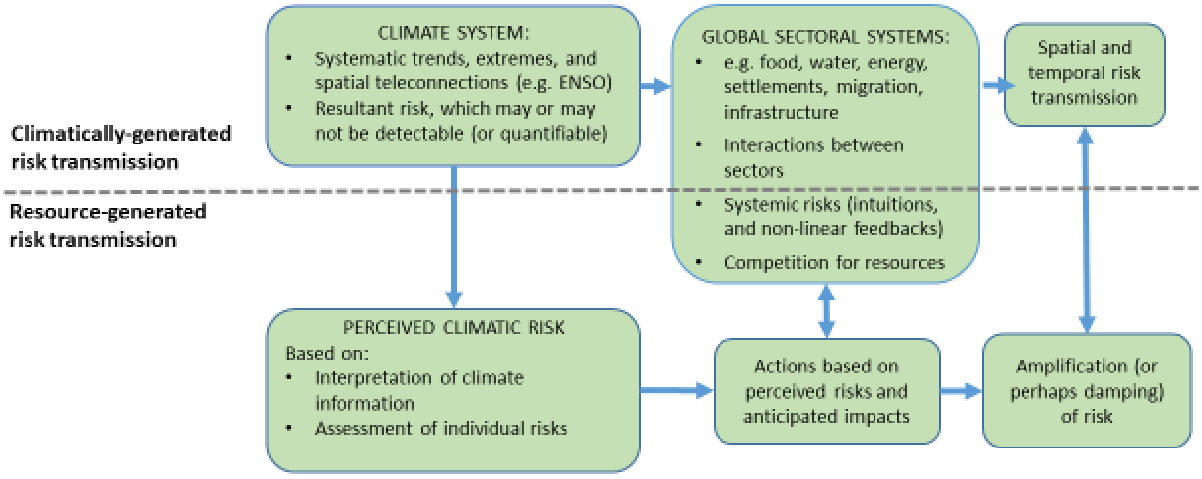

Figure 2. Pathways of resource- and climatically- generated risk transmission. The former is characterised by amplification as a result of systemic risks and/or by perceptions of scarcity and risk (whether or not a real risk exists). Climatically-generated risk transmission is characterised by climate-related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

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 mechanisms is rooted in perception (social risk) and the other is rooted in the climate system.

One impact of the transmission of climatic risks to food security is food price volatility. Fig. 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 Fig. 3, whilst the trigger is climatic, only resource-generated transmission mechanisms are in play. To the extent that climate change outpaces natural and human adaptation [18], 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 Section 4.

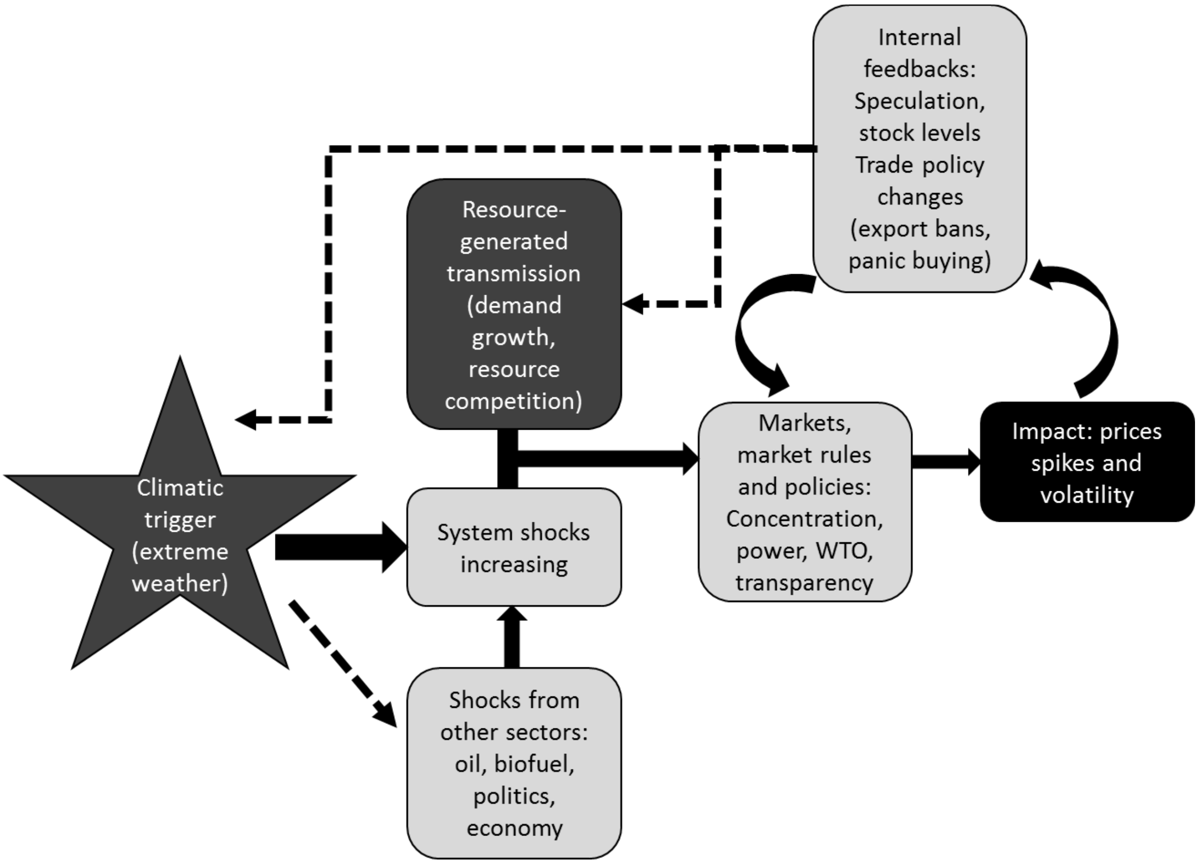

Figure 3. Resource-generated risk amplification through price transmission mechanisms in global agricultural commodity markets. Adapted from refs [12, 19].

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 section 5. Risk can be quantified either by integration of knowledge to produce information on real-world risk, or by focussing on one component of risk (section 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 [19]. 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 (section 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 (section 3c).

3a. 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 synthesise knowledge and improve models [31, 32], thus meeting – at least to some extent – these technical challenges.

Whilst meta-analysis of existing results can be used to summarise 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 [18, 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].

3b. 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 focussing 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 degrees 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].

3c. 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, whilst less precise, can nonetheless be indicatively useful for risk assessment, and under some circumstances can identify substantially different risks than models do, since models may have 'blind spots' due to an inability to capture unknown knowns (see e.g. Fig 3. of ref. 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 civilisations [47] – such as Angkor Wat [48], or the Mayan Civilisation [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 view points, 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) (SRES and RCPs) are based on emissions trajectories and a narrative – the Shared Socio-economic Pathways [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. Whilst 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] focussed on climate change impacts in the United States, with risk transmission only considered explicitly via water resources shared with neighbouring countries. It has been argued that future US assessments need to have a greater focus on risk, beginning with analysis of those decisions that are affected by climate and focussing 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, characterising climatic- vs 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 involves both climatic and resource mechanisms (c.f. Fig. 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, population displacement risk and transboundary water resources 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.

4a. 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 non-linear 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, 19, 60]. Whilst all of these factors interact and each one can be important (Fig. 3), production shortfalls generated by weather extremes are often the initial spark that drives the volatility [19]. For example, a shortfall in supply creates a price signal which markets and governments amplify by export bans that prioritise 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 heat wave 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-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 2007-8, 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 2007-8 food price spike [71].

Analysis of responses to food prices rises in 2010-11 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 austerely, (d) drew on savings and household assets, (e) responded politically through criticism of their governments. Those affected peceived 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 politicised response contributed to food-related civil unrest in a number of countries in 2010/11 [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 5-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 percent 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 Fig. 1). Risks generated by climatic trends can be subtle and hence difficult to identify. For example, time of emergence techniques (section 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 to that in which it is eventually used [18]. 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 likely also the private sector; as well as requiring significant international coordination [2, 18].

4b. 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 continue 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 is 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 both through prior decisions concerning land use and uneven distribution of resources and vulnerability among populations. Reponses 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 either climatically-generated transmission: large-scale droughts, floods or hurricanes can trigger displacement across borders (the weather abroad affects domestic risk directly). There is likely also be a resource-generated transmission mechanism: people are displaced because they lack water, food, 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 ten percent 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 2006-9 [87, 88]. The evidence falls short of risk assessment, however, since 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 in both 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 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.

4c. Cross-sectoral and transboundary risk amplification in water and energy

Linkages between sectors can be a critical part of risk transmission (c.f. upper middle box in Fig. 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 2015-16 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 2015-16 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 Section 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.

5a. Plurality of approaches supported by expert judgment 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-characterised, 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 likely require a different framework to 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 characterised 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 non-linear in nature [112, 113]. The importance of understanding complex topologies for assessing systemic risks is increasingly recognised in human systems [12, 114].

A second characteristic of systemic risk assessments is the ability to successfully synthesise the range of expert judgements. Lessons learnt from IPCC AR5 on this subject include the need for a simple and rigorous framework with practices that minimise biases in expert judgement whilst integrating subjective expert views with quantitative evidence [115]. 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 judgment.

Scenario-based approaches (section 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 minimise risks or costs and maximise benefits. For example, in a future where the world is more regionalised and less globalised [55, 116], 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 section 4) 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 section 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 dependencies and foster adaptive policymaking [118]; and assessment of the implications of path dependency, interactions between adaptation plans, vested interests and global change [120].

5b. 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 recognising 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-organising 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-organising 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 naïve assumptions about the behaviour of government and non-governmental actors in the real-world. They identify five key conditional insights from diverse literatures as follows: whilst international institutions are important, they are challenged by globally networked risks; whilst the international norms evolve slowly, they can in some instances respond rapidly; whilst institutions for international crisis management are critical, they are difficult to reform (even after crisis); whilst stimulating new capacities is important, successful policy initiatives are often difficult to up-scale; and whilst 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 organisations 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.

5c. 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 section 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 section 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 both changes in 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 section 3a). Whilst 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 focusses 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 section 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 dependencies. 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.

5d. 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 is when markets and policy amplify the price signal in a highly non-linear way (see section 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 attenuates rather than amplifies risk?

A second area where improved understanding of societal roles would support risk attenuation is that of decision-making. Section 5a emphasises the role of plurality in improving understanding of risk transmission and building scenarios. Whilst 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, whilst 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 (sections 5a-5c) may yield additional benefits by identifying unforeseen risks (as in the crop breeding case in section 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 Conclusions

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 trans-boundary and trans-sector dimension. Their dynamics differ, and they also interact. Our analysis shows that policies and institutions can attenuate risks significantly through co-operation 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 prioritising 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, focusses on the role of climate versus that of societal responses and perceptions; i.e. climatic- and resource-generated amplification mechanisms. Other framings, developed in section 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.

Additional Information

Information on the following should be included wherever relevant.

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Competing Interests

We have no competing interests.

Authors' Contributions

AJC led and compiled the analyses, based on intellectual input and concepts discussed proposed by all authors and refined amongst all authors. All authors contributed to the writing of the manuscript.

References

[1] Gardiner, S. M. 2011 *A perfect moral storm: the ethical tragedy of climate change*, Oxford University Press: Oxford.

[2] Challinor, A., Adger, W. N., Di Mauro, M., Baylis, M., Benton, T., Conway, D., Depledge, D., Geddes, A., McCorriston, S., Stringer, L., et al. 2016 UK Climate Change Risk Assessment Evidence Report: Chapter 7, International Dimensions. Report prepared for the Adaptation Sub-Committee of the Committee on Climate Change, London.

[3] Rayner, S. & Cantor, R. 1987 How Fair Is Safe Enough? The Cultural Approach to Societal Technology Choice1. *Risk Analysis* **7**, 3-9. (DOI:10.1111/j.1539-6924.1987.tb00963.x).

[4] Hughes, T. P., Barnes, M. L., Bellwood, D. R., Cinner, J. E., Cumming, G. S., Jackson, J. B. C., Kleypas, J., van de Leemput, I. A., Lough, J. M., Morrison, T. H., et al. 2017 Coral reefs in the Anthropocene. *Nature* **546**, 82-90. (DOI:http://dx.doi.org/10.1038/nature22901).

[5] Ackerman, F., DeCanio, S. J., Howarth, R. B. & Sheeran, K. 2009 Limitations of integrated assessment models of climate change. *Climatic Change* **95**, 297-315. (DOI:10.1007/s10584-009-9570-x).

[6] Gardiner, S. M. 2006 A Core Precautionary Principle*. *Journal of Political Philosophy* **14**, 33-60. (DOI:10.1111/j.1467-9760.2006.00237.x).

[7] 2007. *IPCC Fourth Assessment Report: Climate Change 2007 (AR4).*

[8] Challinor, A., Adger, W. & Benton, T. 2017 (In Press) Climate risks across borders and scales. *Nature Climate Change.*

[9] Beale, N., Rand, D. G., Battey, H., Croxson, K., May, R. M. & Nowak, M. A. 2011 Individual versus systemic risk and the Regulator's Dilemma. *Proceedings of the National Academy of Sciences* **108**, 12647-12652. (DOI:10.1073/pnas.1105882108).

[10] Helbing, D. 2013 Globally networked risks and how to respond. *Nature* **497**, 51-59. (DOI:10.1038/nature12047).

[11] Kasperson, J. X., Kasperson, R. E., Pidgeon, N. & Slovic, P. 2003 The social amplification of risk: assessing fifteen years of research and theory. In *The Social Amplification of Risk* (eds. N. Pidgeon, P. Slovic & R. E. Kasperson), pp. 13-46. Cambridge, Cambridge University Press.

[12] Homer-Dixon, T., Walker, B., Biggs, R., Crépin, A.-S., Folke, C., Lambin, E. F., Peterson, G. D., Rockström, J., Scheffer, M., Steffen, W., et al. 2015 Synchronous failure: the emerging causal architecture of global crisis. *Ecology and Society* **20**. (DOI:10.5751/ES-07681-200306).

[13] Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K. C., Gleick, P., Kremen, C., et al. 2015 Systems integration for global sustainability. *Science* **347**. (DOI:10.1126/science.1258832).

[14] Adger, W. N., Eakin, H. & Winkels, A. 2009 Nested and teleconnected vulnerabilities to environmental change. *Frontiers in Ecology and the Environment* **7**, 150-157. (DOI:10.1890/070148).

[15] Kasperson, R. E., Renn, O., Slovic, P., Brown, H. S., Emel, J., Goble, R., Kasperson, J. X. & Ratick, S. 1988 The Social Amplification of Risk: A Conceptual Framework. *Risk Analysis* **8**, 177-187. (DOI:10.1111/j.1539-6924.1988.tb01168.x).

[16] Renn, O., Burns, W. J., Kasperson, J. X., Kasperson, R. E. & Slovic, P. 1992 The Social Amplification of Risk: Theoretical Foundations and Empirical Applications. *Journal of Social Issues* **48**, 137-160. (DOI:10.1111/j.1540-4560.1992.tb01949.x).

[17] Moritz, M. A., Batllori, E., Bradstock, R. A., Gill, A. M., Handmer, J., Hessburg, P. F., Leonard, J., McCaffrey, S., Odion, D. C., Schoennagel, T., et al. 2014 Learning to coexist with wildfire. *Nature* **515**, 58-66. (DOI:10.1038/nature13946).

[18] Challinor, A. J., Koehler, A. K., Ramirez-Villegas, J., Whitfield, S. & Das, B. 2016 Current warming will reduce yields unless maize breeding and seed systems adapt immediately. *Nature Clim. Change*. (DOI:10.1038/nclimate3061).

[19] Tadasse, G., Algieri, B., Kalkuhl, M. & von Braun, J. 2016 Drivers and Triggers of International Food Price Spikes and Volatility. In *Food Price Volatility and Its Implications for Food Security and Policy* (eds. M. Kalkuhl, J. von Braun & M. Torero), pp. 59-82. Cham, Springer International Publishing.

[20] Dutton, J. A. 2002 Opportunities and priorities in a new era for weather and climate services. *Bulletin of the American Meteorological Society* **83**, 1303-1311.

[21] Challinor, A. J., Müller, C., Asseng, S., Deva, C., Nicklin, K. J., Wallach, D., Vanuytrecht, E., Whitfield, S., Ramirez-Villegas, J. & Koehler, A.-K. 2017 Improving the use of crop models for risk assessment and climate change adaptation. *Agricultural Systems*. (DOI:https://doi.org/10.1016/j.agsy.2017.07.010).

[22] Wheeler, T. & von Braun, J. 2013 Climate Change Impacts on Global Food Security. *Science* **341**, 508-513. (DOI:10.1126/science.1239402).

[23] Tachiiri, K. & Shinoda, M. 2012 Quantitative risk assessment for future meteorological disasters. *Climatic Change* **113**, 867-882. (DOI:10.1007/s10584-011-0365-5).

[24] Stern, R. D. & Cooper, P. J. M. 2011 Assessing Climate Risk and Climate Change Using Rainfall Data: A Case Study from Zambia. *Experimental Agriculture* **47**, 241-266. (DOI:doi:10.1017/S0014479711000081).

[25] Scholze, M., Knorr, W., Arnell, N. W. & Prentice, I. C. 2006 A climate-change risk analysis for world ecosystems. *Proceedings of the National Academy of Sciences* **103**, 13116-13120. (DOI:10.1073/pnas.0601816103).

[26] Wiens, J. A., Stralberg, D., Jongsomjit, D., Howell, C. A. & Snyder, M. A. 2009 Niches, models, and climate change: Assessing the assumptions and uncertainties. *Proceedings of the National Academy of Sciences of the United States of America* **106**, 19729-19736. (DOI:10.1073/pnas.0901639106).

[27] Challinor, A., Wheeler, T., Garforth, C., Craufurd, P. & Kassam, A. 2007 Assessing the vulnerability of food crop systems in Africa to climate change. *Climatic Change* **83**, 381-399. (DOI:10.1007/s10584-007-9249-0).

[28] Challinor, A. J., Parkes, B. & Ramirez-Villegas, J. 2015 Crop yield response to climate change varies with cropping intensity. *Global Change Biology*, n/a-n/a. (DOI:10.1111/gcb.12808).

[29] Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., Boote, K. J., Thorburn, P., Antle, J. M., Nelson, G. C., Porter, C., Janssen, S., et al. 2013 The Agricultural Model Intercomparison and Improvement Project

(AgMIP): Protocols and pilot studies. *Agricultural and Forest Meteorology* **170**, 166-182. (DOI:10.1016/j.agrformet.2012.09.011).

[30] Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R. & Chhetri, N. 2014 A meta-analysis of crop yield under climate change and adaptation. *Nature Clim. Change* **4**, 287-291. (DOI:10.1038/nclimate2153).

[31] Maiorano, A., Martre, P., Asseng, S., Ewert, F., Müller, C., Rötter, R. P., Ruane, A. C., Semenov, M. A., Wallach, D., Wang, E., et al. 2016 Crop model improvement reduces the uncertainty of the response to temperature of multi-model ensembles. . *Field Crops Research* **in press**.

[32] Challinor, A., Martre, P., Asseng, S., Thornton, P. & Ewert, F. 2014 Making the most of climate impacts ensembles. *Nature Clim. Change* **4**, 77-80. (DOI:10.1038/nclimate2117).

[33] Vermeulen, S. J., Challinor, A. J., Thornton, P. K., Campbell, B. M., Eriyagama, N., Vervoort, J. M., Kinyangi, J., Jarvis, A., Läderach, P., Ramirez-Villegas, J., et al. 2013 Addressing uncertainty in adaptation planning for agriculture. *Proceedings of the National Academy of Sciences* **110**, 8357-8362. (DOI:10.1073/pnas.1219441110).

[34] Joshi, M., Hawkins, E., Sutton, R., Lowe, J. & Frame, D. 2011 Projections of when temperature change will exceed 2ºC above pre-industrial levels. *Nature Clim. Change* **1**, 407-412. (DOI:10.1038/nclimate1261).

[35] Frame, D., Joshi, M., Hawkins, E., Harrington, L. J. & de Roiste, M. 2017 Population-based emergence of unfamiliar climates. *Nature Climate Change* **7**, 407-411. (DOI:doi:10.1038/nclimate3297).

[36] Hawkins, E. & Sutton, R. 2012 Time of emergence of climate signals. *Geophysical Research Letters* **39**, n/a-n/a. (DOI:10.1029/2011GL050087).

[37] Harrison, P. A., Dunford, R. W., Holman, I. P. & Rounsevell, M. D. A. 2016 Climate change impact modelling needs to include cross-sectoral interactions. *Nature Clim. Change* **6**, 885-890. (DOI:10.1038/nclimate3039).

[38] Watkiss, P. 2011 Aggregate economic measures of climate change damages: explaining the differences and implications. *Wiley Interdisciplinary Reviews: Climate Change* **2**, 356-372. (DOI:10.1002/wcc.111).

[39] Sarofim, M. C. & Reilly, J. M. 2011 Applications of integrated assessment modeling to climate change. *Wiley Interdisciplinary Reviews: Climate Change* **2**, 27-44. (DOI:10.1002/wcc.93).

[40] Piontek, F., Müller, C., Pugh, T. A. M., Clark, D. B., Deryng, D., Elliott, J., Colón González, F. d. J., Flörke, M., Folberth, C., Franssen, W., et al. 2014 Multisectoral climate impact hotspots in a warming world. *Proceedings of the National Academy of Sciences* **111**, 3233-3238. (DOI:10.1073/pnas.1222471110).

[41] Frieler, K., Betts, R., Burke, E., Ciais, P., Denvil, S., Deryng, D., Ebi, K., Eddy, T., Emanuel, K., Elliott, J., et al. 2016 Assessing the impacts of 1.5°C global warming – simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). *Geosci. Model Dev. Discuss.* **2016**, 1-59. (DOI:10.5194/gmd-2016-229).

[42] Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., M\"uller, C., Arneth, A., Boote, K. J., Folberth, C., Glotter, M., Khabarov, N., et al. 2014 Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences of the United States of America* **111**, 3268-3273.

[43] Ewert, F., Rotter, R. P., Bindi, M., Webber, H., Trnka, M., Kersebaum, K. C., Olesen, J. E., van Ittersum, M. K., Janssen, S., Rivington, M., et al. 2015 Crop modelling for integrated assessment of risk to food production from climate change. *Environmental Modelling & Software* **72**, 287-303. (DOI:10.1016/j.envsoft.2014.12.003).

[44] Ruane, A., Rosenzweig, C., Asseng, S., Boote, K., Elliott, J., Ewert, F., Jones, J., Martre, P., McDermid, S., Müller, C., et al. 2017 An AgMIP framework for improved agricultural representation in IAMs. *Environmental Research Letters (Submitted).*

[45] Rippke, U., Ramirez-Villegas, J., Jarvis, A., Vermeulen, S. J., Parker, L., Mer, F., Diekkruger, B., Challinor, A. J. & Howden, M. 2016 Timescales of transformational climate change adaptation in sub-Saharan African agriculture. *Nature Clim. Change* **advance online publication**. (DOI:10.1038/nclimate2947 http://www.nature.com/nclimate/journal/vaop/ncurrent/abs/nclimate2947.html#supplementary-information).

[46] Anderson, A. S., Storlie, C. J., Shoo, L. P., Pearson, R. G. & Williams, S. E. 2013 Current Analogues of Future Climate Indicate the Likely Response of a Sensitive Montane Tropical Avifauna to a Warming World. *PLOS ONE* **8**, e69393. (DOI:10.1371/journal.pone.0069393).

[47] Tainter Joseph, A. 1988 The collapse of complex societies. (Cambridge University Press.

[48] Buckley, B. M., Anchukaitis, K. J., Penny, D., Fletcher, R., Cook, E. R., Sano, M., Nam, L. C., Wichienkeeo, A., Minh, T. T. & Hong, T. M. 2010 Climate as a contributing factor in the demise of Angkor, Cambodia. *Proceedings of the National Academy of Sciences* **107**, 6748-6752. (DOI:10.1073/pnas.0910827107).

[49] Hodell, D. A., Curtis, J. H. & Brenner, M. 1995 Possible role of climate in the collapse of Classic Maya civilization. (

[50] Wright, G., Cairns, G. & Bradfield, R. 2013 Scenario methodology: New developments in theory and practice. *Technological Forecasting and Social Change* **80**, 561-565. (DOI:http://dx.doi.org/10.1016/j.techfore.2012.11.011).

[51] Swart, R., Fuss, S., Obersteiner, M., Ruti, P., Teichmann, C. & Vautard, R. 2013 Beyond vulnerability assessment. *Nature Climate Change* **3**, 942.

[52] Stern, P. C., Ebi, K. L., Leichenko, R., Olson, R. S., Steinbruner, J. D. & Lempert, R. 2013 Managing risk with climate vulnerability science. *Nature Clim. Change* **3**, 607-609. (DOI:10.1038/nclimate1929).

[53] Meissner, P. & Wulf, T. 2013 Cognitive benefits of scenario planning: Its impact on biases and decision quality. *Technological Forecasting and Social Change* **80**, 801-814. (DOI:http://dx.doi.org/10.1016/j.techfore.2012.09.011).

[54] Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M. & Kram, T. 2010 The next generation of scenarios for climate change research and assessment. *Nature* **463**, 747.

[55] O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., et al. 2017 The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change* **42**, 169-180. (DOI:http://dx.doi.org/10.1016/j.gloenvcha.2015.01.004).

[56] Fish, M. & Su, Y. S. 2015 Food Chain Reaction - A Global Food Security Game http://foodchainreaction.org/wp-content/uploads/2016/02/Technical-Report.pdf/.

[57] Warren, R., Watkiss, P., Wilby, R., Humphrey, K., Ranger, N., Betts, R., Lowe, J. & Watts, G. 2016 UK Climate Change Risk Assessment Evidence Report: Chapter 2, Approach and Context. *Report prepared for the Adaptation Sub-Committee of the Committee on Climate Change, London.*

[58] Melillo, J. M., Richmond, T. T. C. & Yohe, G. W. 2014 Climate Change Impacts in the United States: The Third National Climate Assessment. *U.S. Global Change Research Program*, 841. (DOI:doi:10.7930/J0Z31WJ2).

[59] Weaver, C. P., Richard, M., Kristie, E., Peter, G., Paul, S., Claudia, T., Robyn, W. & Joseph, A. 2017 Reframing climate change assessments around risk: recommendations for the U.S. National Climate Assessment. *Environmental Research Letters*.

[60] 2011 Climate trends and global crop production since 1980. *Science* **333**, 616.

[61] Watanabe, M., Shiogama, H., Imada, Y., Mori, M., Ishii, M. & Kimoto, M. 2013 Event Attribution of the August 2010 Russian Heat Wave. *SOLA* **9**, 65-68.

[62] Barriopedro, D., Fischer, E. M., Luterbacher, J., Trigo, R. M. & García-Herrera, R. 2011 The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe. *Science* **332**, 220-224. (DOI:10.1126/science.1201224).

[63] Hoag, H. 2014 Russian summer tops 'universal'heatwave index. *Nature* **16**.

[64] Trenberth, K. E. 2012 Framing the way to relate climate extremes to climate change. *Climatic Change* **115**, 283-290. (DOI:10.1007/s10584-012-0441-5).

[65] Houze Jr, R., Rasmussen, K., Medina, S., Brodzik, S. & Romatschke, U. 2011 Anomalous atmospheric events leading to the summer 2010 floods in Pakistan. *Bulletin of the American Meteorological Society* **92**, 291-298.

[66] Mann, M. E., Rahmstorf, S., Kornhuber, K., Steinman, B. A., Miller, S. K. & Coumou, D. 2017 Influence of Anthropogenic Climate Change on Planetary Wave Resonance and Extreme Weather Events. **7**, 45242. (DOI:10.1038/srep45242
https://www.nature.com/articles/srep45242#supplementary-information).

[67] Wegren, S. K. 2011 Food security and Russia's 2010 drought. *Eurasian Geography and Economics* **52**, 140-156.

[68] Welton, G. 2011 The Impact of Russia's 2010 Grain Export Ban. *Oxfam Research Reports*.

[69] Spratt, S. 2013 Food price volatility and financial speculation. *Future Agricultures* **Working Paper, 47.**

[70] Jones, A. & Hiller, B. 2017 Exploring the Dynamics of Responses to Food Production Shocks. *Sustainability* **9**, 960.

[71] Dawe, D. & Slayton, T. 2010 The world rice market crisis of 2007-2008, The rice crisis: markets, policies and food security, London, Earthsan and FAO, 15-29. (ed. D. D).

[72] Hossain, N. & Green, D. 2011 Living on a Spike: How is the 2011 food price crisis affecting poor people? . *Oxfam Policy and Practice: Agriculture, Food and Land* **11**, 9-56.

[73] Natalini, D., Bravo, G. & Jones, A. W. 2017 Global food security and food riots – an agent-based modelling approach. *Food Security*. (DOI:10.1007/s12571-017-0693-z).

[74] FAO. 2015 Faostat online database, FAOSTAT Online Database, http://faostat3.fao.org/.

[75] 2012 Calibration strategies: a source of additional uncertainty in climate change projections. *Bull. Am. Meteorol. Soc.* **93**, 21.

[76] Defra. 2012 *Food Statistics Pocketbook.* Food & Rural Affairs, London, UK.

[77] 2005 Simulation of the impact of high temperature stress on annual crop yields. *Agric. For. Meteorol.* **135**, 180.

[78] Martin, S., Weerasinghe, S. & Taylor, A. 2014 What is crisis migration? *Forced Migration Review* **45**, 5-9.

[79] Munro, A., Kovats, R. S., Rubin, G. J., Waite, T. D., Bone, A. & Armstrong, B. 2017 Effect of evacuation and displacement on the association between flooding and mental health outcomes: a cross-sectional analysis of UK survey data. *The Lancet Planetary Health* **1**, e134-e141. (DOI:https://doi.org/10.1016/S2542-5196(17)30047-5).

[80] 2008 Investigating the impacts of climate change on wheat in China. *PhD Thesis.*

[81] DeWaard, J., Curtis, K. J. & Fussell, E. 2016 Population recovery in New Orleans after Hurricane Katrina: exploring the potential role of stage migration in migration systems. *Popul Environ* **37**, 449-463. (DOI:10.1007/s11111-015-0250-7).

[82] Looney, R. 2012 Economic impacts of the floods in Pakistan. *Contemporary South Asia* **20**, 225-241. (DOI:10.1080/09584935.2012.670203).

[83] Pelling, M. & Dill, K. 2010 Disaster politics: tipping points for change in the adaptation of sociopolitical regimes. *Progress in Human Geography* **34**, 21-37. (DOI:10.1177/0309132509105004).

[84] Collier, P. & Hoeffler, A. 2004 Greed and Grievance in Civil War. *Oxford Economic Papers* **56**, 563–595. (DOI:10.1596/1813-9450-2355).

[85] Fair, C. C., Kuhn, P. M., Malhotra, N. & Shapiro, J. N. 2017 Natural Disasters and Political Engagement: Evidence from the 2010–11 Pakistani Floods. *Quarterly Journal of Political Science* **12**, 99-141. (DOI:10.1561/100.00015075).

[86] Selby, J., Dahi, O. S., Fröhlich, C. & Hulme, M. 2017 Climate change and the Syrian civil war revisited. *Political Geography* **60**, 232-244. (DOI:https://doi.org/10.1016/j.polgeo.2017.05.007).

[87] Gleick, P. H. 2014 Water, Drought, Climate Change, and Conflict in Syria. *Weather, Climate, and Society* **6**, 331-340. (DOI:10.1175/wcas-d-13-00059.1).

[88] Kelley, C. P., Mohtadi, S., Cane, M. A., Seager, R. & Kushnir, Y. 2015 Climate change in the Fertile Crescent and implications of the recent Syrian drought. *Proceedings of the National Academy of Sciences* **112**, 3241-3246. (DOI:10.1073/pnas.1421533112).

[89] Adger, W. N., Pulhin, J. M., Barnett, J., Dabelko, G. D., Hovelsrud, G. K., Levy, M., Ú. Oswald, S. & Vogel, C. H. 2014 Human security. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* (eds. C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, et al.), pp. XXX-YYY. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

[90] von Uexkull, N., Croicu, M., Fjelde, H. & Buhaug, H. 2016 Civil conflict sensitivity to growing-season drought. *Proceedings of the National Academy of Sciences* **113**, 12391-12396. (DOI:10.1073/pnas.1607542113).

[91] Neumann, B., Vafeidis, A. T., Zimmermann, J. & Nicholls, R. J. 2015 Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment. *PLOS ONE* **10**, e0118571. (DOI:10.1371/journal.pone.0118571).

[92] Barrios Puente, G., Perez, F. & Gitter, R. J. 2016 The Effect of Rainfall on Migration from Mexico to the United States. *International Migration Review* **50**, 890-909. (DOI:10.1111/imre.12116).

[93] Hauer, M. E. 2017 Migration induced by sea-level rise could reshape the US population landscape. *Nature Clim. Change* **7**, 321-325. (DOI:10.1038/nclimate3271 http://www.nature.com/nclimate/journal/v7/n5/abs/nclimate3271.html#supplementary-information).

[94] Jacobs, K. L., Buizer, J. L. & Moser, S. C. 2016 The third US national climate assessment: innovations in science and engagement. *Climatic Change* **135**, 1-7. (DOI:10.1007/s10584-016-1621-5).

[95] Subramanian, A., Brown, B. & Wolf, A. T. 2014 Understanding and overcoming risks to cooperation along transboundary rivers. *Water Policy* **16**, 824-843. (DOI:10.2166/wp.2014.010).

[96] Hoekstra, A. Y. & Mekonnen, M. M. 2012 The water footprint of humanity. *Proceedings of the National Academy of Sciences of the United States of America* **109**, 3232-3237.

[97] Dalin, C., Wada, Y., Kastner, T. & Puma, M. J. 2017 Groundwater depletion embedded in international food trade. *Nature* **543**, 700-704. (DOI:10.1038/nature21403 http://www.nature.com/nature/journal/v543/n7647/abs/nature21403.html#supplementary-information).

[98] Vörösmarty, C. J., Hoekstra, A. Y., Bunn, S. E., Conway, D. & Gupta, J. 2015 Fresh water goes global. *Science* **349**, 478-479. (DOI:10.1126/science.aac6009).

[99] Keller, J., Keller, A. & Davids, G. 1998 River basin development phases and implications of closure *Journal of Applied Irrigation Science* **33**, 145-163.

[100] Allan, J. A. 1998 Virtual Water: A Strategic Resource Global Solutions to Regional Deficits. *Ground Water* **36**, 545-546. (DOI:10.1111/j.1745-6584.1998.tb02825.x).

[101] Keys, P. W., Wang-Erlandsson, L., Gordon, L. J., Galaz, V. & Ebbesson, J. 2017 Approaching moisture recycling governance. *Global Environmental Change* **45**, 15-23. (DOI:https://doi.org/10.1016/j.gloenvcha.2017.04.007).

[102] Conway, D., van Garderen, E. A., Deryng, D., Dorling, S., Krueger, T., Landman, W., Lankford, B., Lebek, K., Osborn, T., Ringler, C., et al. 2015 Climate and southern Africa's water-energy-food nexus. *Nature Clim. Change* **5**, 837-846. (DOI:10.1038/nclimate2735 http://www.nature.com/nclimate/journal/v5/n9/abs/nclimate2735.html#supplementary-information).

[103] Nicholson, S. E. & Kim, J. 1997 The Relationship of the El NiÑo–Southern Oscillation to African Rainfall. *International Journal of Climatology* **17**, 117-135. (DOI:10.1002/(sici)1097-0088(199702)17:2<117::aid-joc84>3.0.co;2-o).

[104] Richard, Y., Trzaska, S., Roucou, P. & Rouault, M. 2000 Modification of the southern African rainfall variability/ENSO relationship since the late 1960s. *Anglais* **16**, 883-895. (DOI:10.1007/s003820000086).

[105] Blunden, J., and D. S. Arndt. 2016 State of the Climate in 2015. *Bull. Amer. Meteor. Soc.* **97**, S1-S275.

[106] Tsidu, M. 2016 Southern Africa between 5° and 30°S [in "State of the Climate in 2015"]. *Bull. Amer. Meteor. Soc.* **97**, S192–S193.

[107] Ashton, P. & Turton, A. 2009 Water and Security in Sub-Saharan Africa: Emerging Concepts and their Implications for Effective Water Resource Management in the Southern African Region. In *Facing Global*

Environmental Change: Environmental, Human, Energy, Food, Health and Water Security Concepts (eds. H. G. Brauch, Ú. O. Spring, J. Grin, C. Mesjasz, P. Kameri-Mbote, N. C. Behera, B. Chourou & H. Krummenacher), pp. 661-674. Berlin, Heidelberg, Springer Berlin Heidelberg.

[108] Olesen, J. E. & Bindi, M. 2002 Consequences of climate change for European agricultural productivity, land use and policy. *European Journal of Agronomy* **16**, 239-262. (DOI:10.1016/s1161-0301(02)00004-7).

[109] Conway, D., Dalin, C. A., Landman, W. & Osborn, T. J. in press Hydropower plans in eastern and southern Africa increase risk of climate related concurrent electricity supply disruption. *Nature Energy*.

[110] Circle of Blue, 2015, http://www.circleofblue.org/waternews/2015/world/zambia-electricity-shortage-highlights-africas-hydropower-shortfalls/

[111] Pope, E. C. D., Buontempo, C. & Economou, T. 2017 Quantifying how user-interaction can modify the perception of the value of climate information: A Bayesian approach. *Climate Services* **6**, 41-47. (DOI:https://doi.org/10.1016/j.cliser.2017.06.006).

[112] Pearl, J. 2001 Direct and indirect effects. In *Proceedings of the Seventeenth conference on Uncertainty in artificial intelligence* (pp. 411-420. Seattle, Washington, Morgan Kaufmann Publishers Inc.

[113] Wootton, J. T. 1994 The Nature and Consequences of Indirect Effects in Ecological Communities. *Annual Review of Ecology and Systematics* **25**, 443-466. (DOI:10.1146/annurev.es.25.110194.002303).

[114] May, R. M. 2013 Networks and webs in ecosystems and financial systems. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **371**. (DOI:10.1098/rsta.2012.0376).

[115] Mach, K. J., Mastrandrea, M. D., Freeman, P. T. & Field, C. B. 2017 Unleashing expert judgment in assessment. *Global Environmental Change* **44**, 1-14. (DOI:https://doi.org/10.1016/j.gloenvcha.2017.02.005).

[116] Ipcc. 2014 Summary for Policymakers. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, et al.), pp. 1-32. Cambridge, United Kingdom, and New York, NY, USA, Cambridge University Press.

[117] Kok, K., van Vliet, M., Bärlund, I., Dubel, A. & Sendzimir, J. 2011 Combining participative backcasting and exploratory scenario development: Experiences from the SCENES project. *Technological Forecasting and Social Change* **78**, 835-851. (DOI:10.1016/j.techfore.2011.01.004).

[118] Haasnoot, M., Kwakkel, J. H., Walker, W. E. & ter Maat, J. 2013 Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change* **23**, 485-498. (DOI:https://doi.org/10.1016/j.gloenvcha.2012.12.006).

[119] Kasprzyk, J. R., Nataraj, S., Reed, P. M. & Lempert, R. J. 2013 Many objective robust decision making for complex environmental systems undergoing change. *Environmental Modelling & Software* **42**, 55-71. (DOI:https://doi.org/10.1016/j.envsoft.2012.12.007).

[120] Wise, R. M., Fazey, I., Stafford Smith, M., Park, S. E., Eakin, H. C., Archer Van Garderen, E. R. M. & Campbell, B. 2014 Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change* **28**, 325-336. (DOI:https://doi.org/10.1016/j.gloenvcha.2013.12.002).

[121] Walker, B., Barrett, S., Polasky, S., Galaz, V., Folke, C., Engström, G., Ackerman, F., Arrow, K., Carpenter, S., Chopra, K., et al. 2009 Looming Global-Scale Failures and Missing Institutions. *Science* **325**, 1345-1346. (DOI:10.1126/science.1175325).

[122] Brownstein , J. S., Freifeld , C. C. & Madoff , L. C. 2009 Digital Disease Detection — Harnessing the Web for Public Health Surveillance. *New England Journal of Medicine* **360**, 2153-2157. (DOI:10.1056/NEJMp0900702).

[123] Choi, H. & Varian, H. A. L. 2012 Predicting the Present with Google Trends. *Economic Record* **88**, 2-9. (DOI:10.1111/j.1475-4932.2012.00809.x).

[124] Palen, L., Anderson, K. M., Mark, G., Martin, J., Sicker, D., Palmer, M. & Grunwald, D. 2010 A vision for technology-mediated support for public participation \& assistance in mass emergencies \& disasters. In *Proceedings of the 2010 ACM-BCS Visions of Computer Science Conference* (pp. 1-12. Edinburgh, United Kingdom, British Computer Society.

[125] Galaz, V., Tallberg, J., Boin, A., Ituarte-Lima, C., Hey, E., Olsson, P. & Westley, F. 2017 Global Governance Dimensions of Globally Networked Risks: The State of the Art in Social Science Research. *Risk, Hazards and Crisis in Public Policy* **8**, 4-27. (DOI:10.1002/rhc3.12108).

[126] Centeno, M. A., Nag, M., Patterson, T. S., Shaver, A. & Windawi, A. J. 2015 The Emergence of Global Systemic Risk. *Annual Review of Sociology* **41**, 65-85. (DOI:10.1146/annurev-soc-073014-112317).

[127] Park, C. E., Jeong, S. J., Joshi, M., Osborn, T., Ho, C. H., Piao, S., Chen, D., Liu, J., Yang, H., Park, H., et al. 2018 Keeping global warming within 1.5ºC restrains emergence of aridification. *In Press in Nature Climate Change*. (DOI:DOI: 10.1038/s41558-017-0034-4).

[128] Loarie, S. R., Duffy, P. B., Hamilton, H., Asner, G. P., Field, C. B. & Ackerly, D. D. 2009 The velocity of climate change. *Nature* **462**, 1052-1055. (DOI:http://dx.doi.org/10.1038/nature08649).

[129] Grafton, R. Q., McLindin, M., Hussey, K., Wyrwoll, P., Wichelns, D., Ringler, C., Garrick, D., Pittock, J., Wheeler, S., Orr, S., et al. 2016 Responding to Global Challenges in Food, Energy, Environment and Water: Risks and Options Assessment for Decision-Making. *Asia & the Pacific Policy Studies* **3**, 275-299. (DOI:10.1002/app5.128).

Figure captions

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).

Figure 2. Pathways of resource- and climatically- generated risk transmission. The former is characterised 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 characterised 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.

Figure 3. Resource-generated risk amplification through price transmission mechanisms in global agricultural commodity markets. Adapted from refs [12, 19].