One Earth

Perspective

A framework for complex climate change risk assessment

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https://doi.org/10.1016/j.oneear.2021.03.005

SUMMARY

Real-world experience underscores the complexity of interactions among multiple drivers of climate change risk and of how multiple risks compound or cascade. However, a holistic framework for assessing such complex climate change risks has not yet been achieved. Clarity is needed regarding the interactions that generate risk, including the role of adaptation and mitigation responses. In this perspective, we present a framework for three categories of increasingly complex climate change risk that focus on interactions among the multiple drivers of risk, as well as among multiple risks. A significant innovation is recognizing that risks can arise both from potential impacts due to climate change and from responses to climate change. This approach encourages thinking that traverses sectoral and regional boundaries and links physical and socio-economic drivers of risk. Advancing climate change risk assessment in these ways is essential for more informed decision making that reduces negative climate change impacts.

INTRODUCTION

We live in a highly networked world where multiple drivers of climate change risk interact, as do the risks themselves. Connections among socio-economic, environmental, and technological systems transmit risk from one system or sector to another, creating new risks or exacerbating existing ones.[1–5] For example, global warming of 2°C above pre-industrial levels is projected to reduce global yields of staple crops by 5%–20%.[6] Greenhouse gas mitigation options can also increase food insecurity if bioenergy crops displace food crops, or can lead to biodiversity loss from land use change for cropping and afforestation.[7] Concurrently, trade networks link distant food systems together and can thus compensate for reduced food security, but they can also create new risks of global impacts, such as multiple-breadbasket failure;[8] more rapid spread of disease,

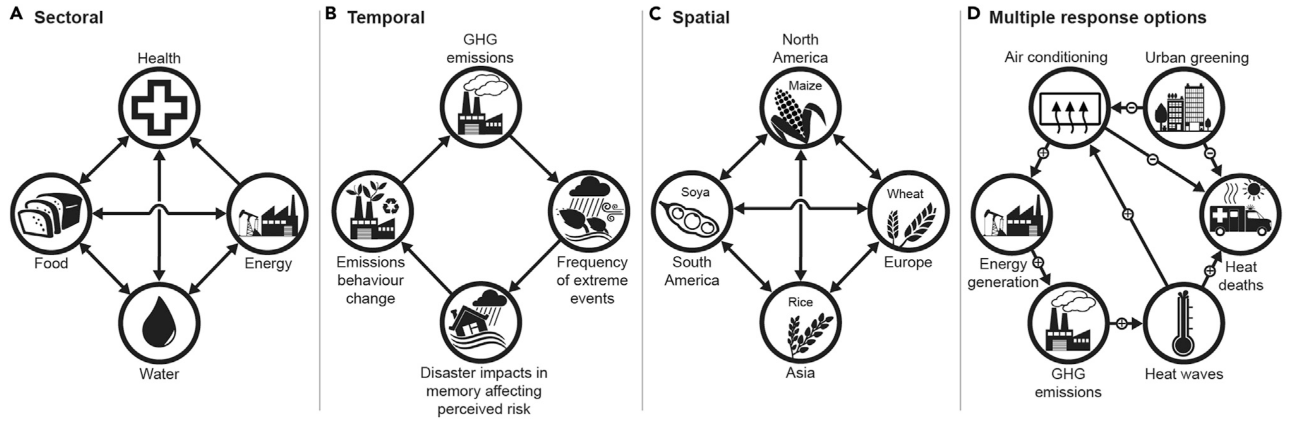

Figure 1. Multiple material and conceptual boundaries exist across which interactions can dampen or amplify climate change risks
Examples include (A) cross-sectoral interactions such as between water, energy, food, and health; (B) temporal lags such as between climate extremes and behavior change; (C) spatial telecoupling such as for food trade networks and breadbasket failures; and (D) interactions of multiple mitigation and adaptation response options such as urban greening and fossil-fueled air conditioning as responses to extreme heat.

pests, and other invasive species;[9] and new threats to local food security from changes in commodity prices caused by policy choices made elsewhere.[10] These interactions include both those risks caused by climate change and those involving responses to climate change through adaptation and mitigation[11] (hereafter collectively termed climate change risks), where risk is understood to refer to the potential for negative or positive outcomes for human or ecological systems.

We use the term complex to communicate the diversity of interactions among sectors and systems[12] that can amplify or reduce climate change risks. Although risk assessment approaches that consider such interactions and networks are beginning to be used,[13–15] many climate change risk assessments often ignore interactions in part or in full. In doing so, they may significantly misestimate risk, such as when single-sector models of food production misrepresent the direction, magnitude, and spatial pattern of risk compared with analyses that consider cross-sectoral interactions.[12,16] However, for convenience and tractability, analysts and managers tend to break risk assessments into silos,[17] often taking a component-oriented, rather than interaction-oriented, view.[1] For example, the Intergovernmental Panel on Climate Change (IPCC) typically divides its assessment into three separate working groups focused on (1) physical climate change; (2) climate impacts, vulnerability, and adaptation responses (by sector and region); and (3) emissions mitigation (by sector). This approach is useful for synthesizing thousands of discipline-specific studies and also reflects the largely sectoral approach of many governments. Cross-working-group IPCC assessments, such as special reports on managing the risk of extreme events and disasters to advance climate change adaptation (SREX),[18] global warming of 1.5°C,[6] oceans and cryosphere,[11] and climate change and land,[5] help to develop more integrated approaches to risk. However, by tending to divide risk assessment into individual sectors, regions, asset classes, or types of response options, assessments can miss important interactions that generate climate change risk.[12,19]

Multiple material and conceptual boundaries exist that can constrain the assessment of climate change risk. Four major types are sectoral, temporal, spatial, and response-option boundaries (Figure 1). Interactions across these boundaries often amplify or reduce risk relative to when interactions are ignored.[20,21] Indeed, recent evidence indicates how some of the most severe climate change impacts, such as those from deadly heat or sudden ecosystem collapse, are strongly influenced by interactions across multiple sectoral, regional, and response-option boundaries.[3,22] Similarly, how governance or institutional systems implementing climate change responses act across these boundaries also affects the nature of risk.[23] While in some cases these interacting effects may have small impacts, in many situations the risks cannot be understood without considering these interactions.[14] For instance, many water agencies' long-range investment plans are much more vulnerable to the interactions of climate change with other socio-economic factors than to the physical impacts of a changing climate on their own.[24–26] Accounting for these multiple complexities is necessary for assessments tasked with informing national governments on climate change risks, as well as for understanding and managing risks at more local scales, such as cities, or across scales in the private sector.[14]

In this perspective, we synthesize recent work describing complex climate change risk—such as concepts of compound, connected, and cascading interactions—and reflect on the consequences for risk assessment and response. We then establish a framework for risk assessment that encompasses increasing levels of complexity by including interactions among multiple drivers of climate change risk (including adaptation and mitigation responses), as well as among multiple risks. We demonstrate the framework using diverse case studies from cities, fisheries, and finance to illustrate how risk assessments can better consider and categorize complex risk and thus enable more informed and effective responses.

WHERE ARE WE NOW?

Risk in recent climate change assessments has been defined as the potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives

Table 1. Complex risk terms with and without an IPCC definition

Types of complex risk with IPCC definition	
Compound risk	compound risks arise from the interaction of hazards, which can be characterized by single extreme events or multiple coincident or sequential events that interact with exposed systems or sectors[28]
Emergent risk	a risk that arises from the interaction of phenomena in a complex system; for example, the risk caused when geographic shifts in human population in response to climate change lead to increased vulnerability and exposure of populations in the receiving region[29]
Types of complex risk with no IPCC definition	
Aggregate risk	the accumulation of independent determinants of risk[35]
Amplified risk	the substantial enhancement of background risk through combination or concentrations of determinants of risk in time or space[36]
Cascading risk	one event or trend triggering others; interactions can be one way (e.g., domino or contagion effects) but can also have feedbacks; cascading risk is often associated with the vulnerability component of risk, such as critical infrastructure[1,22,37,38]
Interacting risk	the combinations of hazards and their reciprocal influences between different factors and coincidences among environmental drivers[38]
Interconnected risk	the complex interactions among human, environment, and technological systems with physical interdependencies that are closely linked with interconnected social interactions[38]
Interdependent risk	complex systems involve interactions and interdependencies that cannot be separated and lead to a range of unforeseeable risks[39]
Multi-risk	the whole risk from several hazards, taking into account possible hazards and vulnerability interactions entailing both multi-hazard and multi-vulnerability perspectives[40]
Systemic risk	systemic risk results from connections between risks (networked risks), where localized initial failure could have disastrous effects and cause, at its most extreme, unbounded damage[4]

associated with such systems.[27] For example, a climate hazard, such as a heatwave, interacts with human exposure and vulnerability, creating risk to human health. However, many new descriptors are emerging to convey the complexity of risks from climate change. To assess the extent to which this development represents the emergence of a common understanding of complex risk in climate change research and in policy-relevant risk assessments, we analyzed the special reports released for the IPCC's sixth assessment cycle: special reports on global warming of 1.5°C,[6] oceans and cryosphere,[11] and climate change and land[5] (see experimental procedures). These special reports reflect the most recent global synthesis of climate change risks and are intended to cut across the traditional IPCC working group divisions in their assessment. We supplemented this with a review of types of complex risk in peer-reviewed literature since 2015 (see supplemental information).

Our analysis shows that the climate change research community has not yet achieved a consistent framework for assessment of complex climate change risks. The IPCC acknowledges risks can aggregate from multiple sectors,[12] but has only two glossary definitions for types of complex risk, namely, compound risk[28] and emergent risk[29] (Table 1). Moreover, the IPCC notion of compound risk focuses most on the interaction of climate hazards determining a risk[28] and complex risk terms were most often applied to the hazard determinant of a risk. This aligns with a growing research field on climate hazard interactions,[2,30–33] such as heavy precipitation coinciding with a storm surge to increase likelihood of flooding,[34] often termed compound weather or climate events.[31] At least a dozen other terms have been used in recent IPCC special reports to describe differing degrees of complexity for each risk determinant—hazard, exposure, and vulnerability—with some terms applied to multiple determinants of risk, as well as to risk from climate change (Figure 2 and Table 1). Typically, the usage of these terms is not aligned with a particular risk typology and is instead reflective of individual author choices, making a consistent interpretation and synthesis difficult to achieve (Tables S1 and S3). The descriptions of risk are also generally narrowly construed, considered to unfold over a relatively short period of time and are limited in scope to a subset of determinants of risk.

Furthermore, in the existing IPCC framework, risk has been framed predominantly in the context of potential climate change impacts.[11] Risk in the context of climate change adaptation and mitigation responses,[41] such as the financial, political, reputational, and technological risk related to mitigation or the potential for adverse outcomes from maladaptation,[42] has been identified and discussed in the literature but not yet integrated with the overall IPCC risk framework. Rather, the risks associated with responses, such as competition for resources between different adaptation and mitigation options or risk from increased policy instability, are presented and discussed separately.[5,43] However, real-world decisions do often represent trade-offs across those different risks. For example, a policymaker concerned with coastal hazards has to consider the risks from sea-level rise to coastal properties as well as the risk to policy stability and personal electoral fortunes if a sufficiently large or vocal segment of the population does not support a proposed coastal hazard management plan.[44,45] Without clear specification of risk types and an inclusive framework for integrating more complexity into risk assessment, there is a danger that perceptions of climate change risk remain siloed and thus that coherent responses will not emerge.

Beyond IPCC, multiple terms have been used to describe complex risk (Tables 1 and S3). Many of these terms focus on

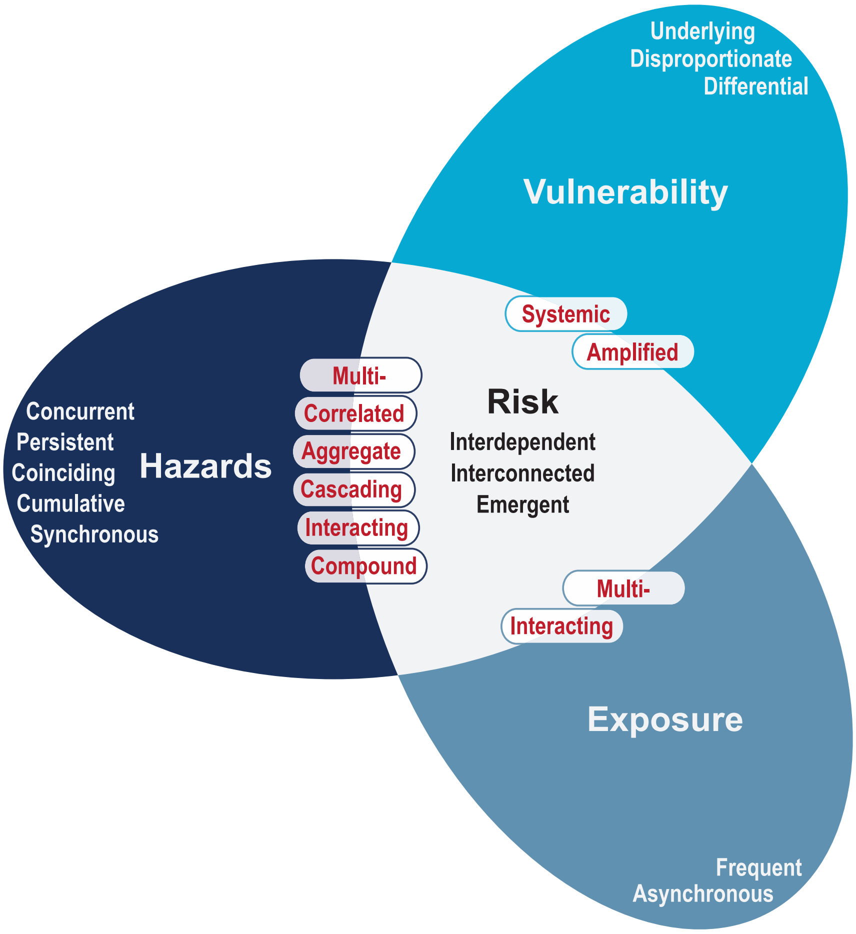

Figure 2. The diversity of complex climate change risk terminology
Terms used to describe complex climate change risk in recent IPCC Special Reports mapped onto the IPCC risk framework used in these IPCC Special Reports. White text shows terms used to describe a given determinant of risk (that is, hazard, exposure, and vulnerability). Black text shows terms used to describe complex risk. Red text highlights terms that have been used to describe both risk and a determinant of risk, such as "compound risk" and "compound hazard." Note that this visual depiction of risk terminology does not include the role of responses to climate change affecting risk determinants or existing risks or in driving new risks through positive or negative side effects of responses.

climate hazards. However, the boundaries among these definitions can blur, and concepts of complex climate change risk continue to evolve.[30,31] Although some definitions refer only to hazards or vulnerability, others take a more integrated perspective on interacting human and environmental systems.[1,37] Overall, these approaches indicate that risk may arise from a number of pathways created by interacting drivers, and that understanding the potential for either positive or negative outcomes[46] and their severity requires appreciation of this network of interactions.[30,31,47] These interactions may include events attributed to anthropogenic climate change, such as a false spring;[31] other human-induced events, such as conflict;[48] preconditions of risk, such as saturated soil, which compounds extreme rainfall to affect flooding;[31] and the systemic vulnerability of societies reliant on complex electricity, communication, and transportation networks.[14,30,31] Other climate assessments are also acknowledging complex risks; for example, multi-sector risk assessment and management in the US Fourth National Climate Assessment,[14] risk to health from multi-exposure pathways in the US Global Change Research Program Climate and Health Assessment,[49] interacting risks in the UK Climate Change Risk Assessment,[13] and globally interconnected risks in the Global Risk Report.[15] The need for transdisciplinary approaches to complex climate change risk has also seen the development of new collaborations such as the My Climate Risk Activity of the World Climate Research Programme[50] and Future Earth Risk Knowledge Action Network.[51] However, there remains no common framework for assessment of complex climate change risks.

This analysis of IPCC special reports and other recent literature highlights three important gaps where a more holistic approach to climate change risk assessment is needed. First, interacting climate hazards are now a key focus for risk assessment, especially for extreme events such as concurrent heat and drought; indeed, the IPCC definition of compound risk focuses on "interaction of hazards."[28] However, this physical science effort on hazards has not yet been integrated with the multiple interactions among ecological, social, and economic drivers of exposure and vulnerability. For instance, low-income workers are often employed outdoors and live in poorly ventilated housing, spend a greater portion of their income on healthcare, and lose relatively more from missing a day of work, all making them more vulnerable and exposed to morbidity and mortality from heat waves.[52] Although integrating quantitative and qualitative knowledge of interactions between physical, ecological, and social systems remains challenging, knowledge co-production approaches to complex risk assessment that use integrated risk assessment models,[53,54] storylines, and scenario planning can highlight interactions across system boundaries that generate risk not evident from more conventional climate impact projections.[31,55,56]

Second, responses to risk are often excluded as drivers of risk even though they play a key role in driving potential outcomes, including inaction, and are well recognized in financial and policy domains.[37,57] Holistic consideration of risks related to climate change impacts involving the real and perceived risks associated with response options is necessary in risk management and decision-making processes.[53,58] Understanding response options as part of climate change risk better explains why decision makers sometimes do not take actions to reduce risk arising from climate hazards, for example, given risks related to

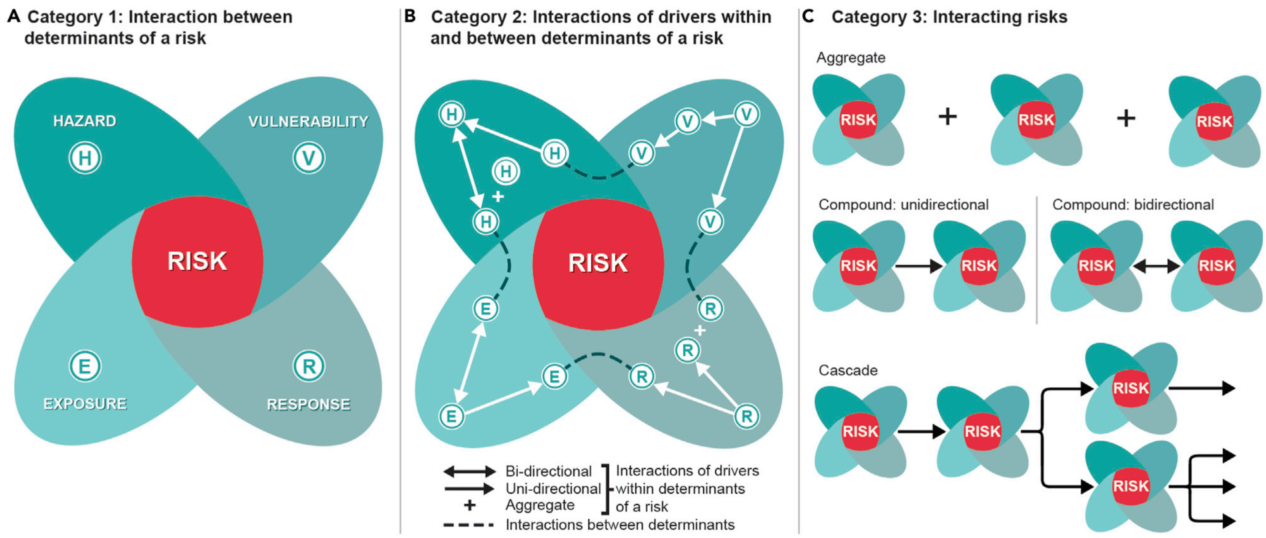

Figure 3. Three categories of increasingly complex climate change risk

(A) Category 1: interactions among single drivers (small circles) for each determinant of a risk, namely hazard, vulnerability, exposure, and response to climate change.

(B) Category 2: interactions of multiple drivers (e.g., compounding vulnerabilities of education and income) within each determinant of risk, as well as among the determinants of a risk.

(C) Category 3: interacting risks.

Across categories 2 and 3, compounding and cascading interactions, together with aggregations, generate increasing complexity for risk assessment. We use "determinant" to refer to hazard, vulnerability, exposure, and response, within which the term "driver" refers to individual components, such as heavy precipitation (a driver within the hazard determinant) or access to shelter (a driver within the vulnerability determinant), that interact to affect the overall risk (e.g., flood mortality).

stranded financial assets,[37] reputation among core constituents,[59] or reliance on novel but untested technological solutions.[60–62] This broader framing of potential trade-offs and co-benefits from interacting responses is essential in the context of multiple interlinked sustainability goals, including stabilizing the climate, reducing hunger, protecting biodiversity, and improving human health.[63] Including climate change responses as potential drivers of risk expands the scope of risk assessment to accommodate positive and beneficial outcomes, not just negative, adverse ones. This is vital for making informed responses more transparent and actionable within complex social decision-making structures,[54,64] where stakeholders attach different weights to the diversity of positive and negative consequences that can arise from both action and inaction.

Third, risk assessment needs to include interactions among multiple risks, not just among the determinants of a risk. Risk has come to be framed in singular terms such as compound risk,[28] cascading risk,[38] or multi-risk[40] when referring to how multiple drivers of a risk interact. However, as the collision of climate change and the coronavirus disease 2019 (COVID-19) pandemic has shown, the interaction of multiple risks can overwhelm the capacity to respond.[65] For example, in 2020, communities in the United States, India, Fiji, and Bangladesh faced evacuation from flooding and tropical cyclones at the same time as social distancing or stay-at-home orders were in place.[65,66] In Zimbabwe, consecutive droughts followed by an unseasonal outbreak of African migratory locusts[67] left millions at risk of acute food insecurity during June–September 2020, while the COVID-19 pandemic made social distancing at communal water and food distribution points very difficult.[68] In turn, climate change is also projected to worsen existing risk of undernutrition or to change the geography of future infectious disease outbreaks.[69,70] Considering interactions among these multiple risks shifts risk assessment from a concentration on individual climate hazards or interactions of hazards as a single event, such as a cyclone, to a set of multiple events interacting continuously with evolving social and economic conditions.

A WAY FORWARD: CATEGORIES OF COMPLEX RISK

Across the suite of terms that have been applied to climate change risk for human and natural systems, there is a commonality: an interaction or aggregation of the determinants of risk—hazard, exposure, and vulnerability—and of multiple risks. We propose an expanded assessment approach that considers responses as an additional determinant of risk and emphasizes what these interactions are (compound, cascade, and aggregate) and where and how they originate. This approach makes the details of interactions within and among determinants of risk, as well as among multiple risks, explicit and thus can help guide more detailed and accurate risk assessment.

We propose that climate change risk assessment can be organized into three categories of increasing complexity based on whether it considers (1) only a single driver for each determinant of risk, (2) multiple interacting drivers within determinants of risk, and (3) interacting risks. We use determinant to refer to hazard, vulnerability, exposure, and response, within which the term driver refers to individual components of these, such as temperature (a driver within the hazard determinant) or income (a driver within the vulnerability determinant), that interact to affect the overall nature of a risk, such as heat mortality.

Based on these criteria, category 1 largely reflects the status quo of existing climate risk assessments[5,6,11] where a single driver for each of climate hazard, vulnerability, and exposure interact (Figure 3A). However, category 1 goes further by explicitly recognizing that a response to climate change can also be a driver of risk.

Even for category 1, the complexity of climate change risk is often only partly accounted for in existing risk assessments. For instance, multiple studies project increased risk from dangerous heat for people or biodiversity based on their exposure but do not also consider a driver for vulnerability or responses to heat stress.[71,72] For some risks, responses to climate change may be the dominant driver of potential outcomes. It is important to note that a response, as we define it here, can be a human intervention directly targeting the risk being assessed, such as irrigation to reduce risk to food security from heat,[73,74] but can also be an adaptation response in another sector[12] or a greenhouse gas mitigation project that affects the risk being assessed, such as expansion of conservation areas for biodiversity or of bioenergy crops that also affect food security.[7] This inclusion of how a response in one sector or region can drive another risk that the response action had little or no intention of influencing is an important feature of an effective assessment approach for complex climate change risk. The role of climate change responses in driving risks is not limited to unintended consequences, though: a decision-maker might very consciously accept an increased risk elsewhere as long as a climate change response delivers a solution to that decision maker's core concern. Clearer understanding and recognition of different people, populations, and ecosystems being affected by different responses,[75] including disproportionate effects, can help us better understand and characterize such risk trade-offs and the values that underpin such choices. Lastly, non-human response can also be included, such as migration of species in response to temperature change.[76]

Although adaptive capacity, as the capability to respond, has been conceptualized as a component of vulnerability since the IPCC Third Assessment Report,[77] distinguishing between responses and vulnerability highlights specific response actions available to decision makers that drive potentially negative or positive outcomes. These options include incremental or transformative actions (both reactive and proactive) that aim to manage change,[78] as well as the consequences of inaction or responses noted as maladaptation.[79] For example, mitigation and adaptation responses carry the potential for positive and adverse consequences, including through multiple trade-offs and co-benefits with other sustainable development goals, and thereby affect the overall nature and complexity of risk.[80,81] The inclusion of response in risk assessment also allows for greater understanding of the relationship between climate change risk and resilience because responses are a key part of the governance and learning about the feedbacks that shape social-ecological systems.[82] As such, the inclusion of response as a determinant of risk helps further the foundations for a framework-level integration of concepts of climate resilient development pathways and climate change risk within climate change assessments.

Category 2 is distinguishable from category 1 because it considers interactions among multiple risk drivers both within and across the determinants of a risk (Figure 3B). For example, multiple hazard drivers, such as concurrent heat and drought, interact with each other to increase the severity of risk.[2] Research on these and other examples of interdependence among hazard drivers is growing, including the development of typologies for compound weather and climate events.[31,32] These approaches fit within category 2, but category 2 expands this risk assessment space by highlighting the need for equal attention to interactions among multiple drivers of vulnerability, exposure, and responses. Such interactions include those among the multiple drivers of vulnerability in the form of gender, age, and race that increase risk of mortality and morbidity from extreme heat,[52] or the interactions among multiple mitigation and adaptation response options, such as city trees mitigating urban heat islands and thereby reducing energy use from air conditioning.[83] Interactions among individual drivers can be uni- or bidirectional. We use the term compound to describe these interaction types because it is increasingly widely used in the literature, including for interacting climate hazards,[30,31] and is neutral with respect to whether interactions amplify positive or negative risk outcomes. Risk can also be affected by the aggregation of multiple independent drivers, such as exposure to heat being increased for outdoor workers who also live in the tropics.[84] The diversity of interactions in category 2 makes it highly complex, comprising interconnections among drivers of risk across human, natural, and technological systems.

Category 3 considers, additionally, the interactions of multiple risks, including both those associated with climate change and those related to other drivers. For example, a multi-breadbasket failure can affect financial, food, and human security through major financial losses to agricultural insurers globally and enhanced potential for civil unrest.[85] Similarly, regions that rely on expanding and intensifying livestock production for rural development could face multiple risks from climate change impacts on feed sources, shifting consumer preferences for alternative protein sources, along with more variable commodity prices linked to increased speculation on bioenergy markets.[86] Risk assessment in category 3 is inherently cross-sectoral and offers opportunities to link with a growing methodology on nexus approaches to sustainable development that simultaneously examine multiple sectors,[12] such as the food-energy-water-health nexus.[21,87] This focus on interactions among multiple risks across different sectors and regions is important because they are a reality people need to manage regardless of the level of quantitative assessment available to inform decision making.[30,56] If each risk is assessed independently, the severity of individual risks and of the overall risk landscape can be underestimated.[37,40,88] In category 3, each risk may have its own set of drivers for hazard, exposure, vulnerability, and responses, but these can also be shared between risks. Interactions among risks can be uni- or bidirectional in nature and are referred to as compounding interactions, such as risk of biodiversity loss compounding risk of food insecurity and risk to health.[89] In contrast, cascades are defined as one risk triggering multiple other risks in a proliferation of interactions,[1,22,38] such as the cascade of the risk of tree death from drought affecting the risks to property and to human

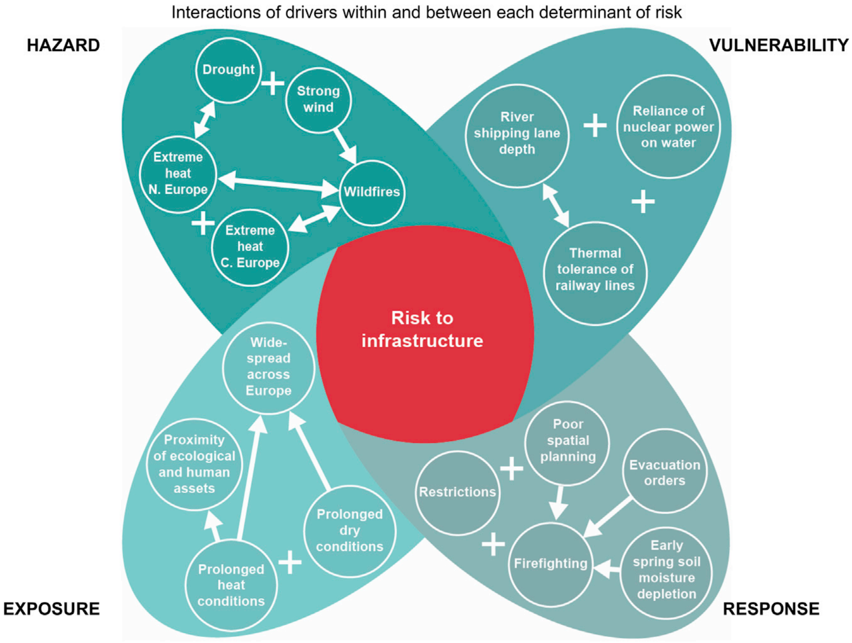

Figure 4. Complex interactions that generated risk to infrastructure during the 2018 European heatwave
Arrows indicate interactions and addition signs indicate aggregation of the individual drivers of risk.

health from wildfires that affects the risks to property, freshwater ecosystems, and to human life from landslides.[30,90,91]

Across all three categories, the different temporal and spatial scales over which drivers of risk, as well as multiple risks, interact require consideration of when and where interactions augment or reduce risk. For example, a risk may increase through temporal compounding when hazard drivers interact over time, such as when the succession of heavy precipitation events connected to the same large-scale climate system in a region can result in flooding.[31] In contrast, temporal or spatial aggregation occurs when the risk drivers are independent of each other, such as the co-occurrence of a wildfire and an earthquake.[92] These same dynamics apply to the interaction or aggregation of multiple risks. For instance, in the humanitarian field, risk of violent conflict interacts over time and space with risk of famine to determine where and when humanitarian relief workers can act.[93] More generally, climate change in the form of slow-onset events and short-term shocks will continue to alter risk profiles over time,[94] as will the temporal dynamics of response options affected by inertia in their implementation or the time taken to reach adaptation limits.[95] As such, shifting to a more dynamic perspective of risk over time and space can help focus more attention on interactions among the various response options required to facilitate recovery and for risk management.[92,94]

FROM ASSESSMENT TO INFORMED RESPONSE

To inform decision making, assessment of complex climate change risk will often require consideration of the four determinants of risk (category 1), the multiple interacting risk drivers within each determinant (category 2), as well as interacting risks (category 3). We suggest scoping risk assessment to one of these categories presented, and describing interactions as either aggregate, compound, or cascading (Figure 3). Building from available research and incomplete information, climate change risk assessment may often begin at lower levels of complexity but should be clear about the need to regularly update risk assessments based on new knowledge of interacting risk drivers and interacting risks, including the role of responses to real and perceived risk.

Here we use examples that bridge from present to future risks to show how complex climate change risk assessment can better support approaches to reduce negative risk outcomes. The following cases demonstrate the nature of interacting risks from a broad range of sectors and how a category 3 approach builds on category 2 and category 1, thereby better enabling risk assessment that considers interconnected socio-economic, environmental, and technological systems that generate climate change risk.

Complex climate risk during the 2018 European heatwave

Although assessment of climate change risk will often begin with category 1, stopping there has potentially severe limitations for risk assessment and response. This is illustrated by understanding interactions that generated risk during the case of the 2018 European heatwave. Between May and August 2018, different sub-regions of Europe experienced multiple, concurrent heat extremes that were compounded by severe drought conditions.[33,96,97] Low water levels in rivers led to restrictions for shipping, nuclear power plants were shut down because of insufficient water for cooling, and railway lines buckled under the heat.[98] Crop yield reductions of up to 50% were reported from Central and Northern Europe alongside losses in the livestock sectors.[33,99] A category 1 assessment of this case concentrates on a subset of interactions for a single risk. For example, risk to transport can be described as the interaction of extreme heat (hazard), thermal tolerance of rail infrastructure (vulnerability), the length of time rail infrastructure experienced prolonged heat conditions (exposure), and how low water levels due to drought resulted in restrictions imposed on shipping, an alternative transport mode to rail (response).[98] Category 1 assessments like this could be conducted for each of the domains of value, such as tourism, electricity generation, or agricultural production.

However, a category 1 assessment excludes key information because the severity of risk was often determined by interactions among multiple drivers within each determinant of a risk, better described by a category 2 climate change risk assessment (Figure 4). For example, the interacting drivers of strong winds,

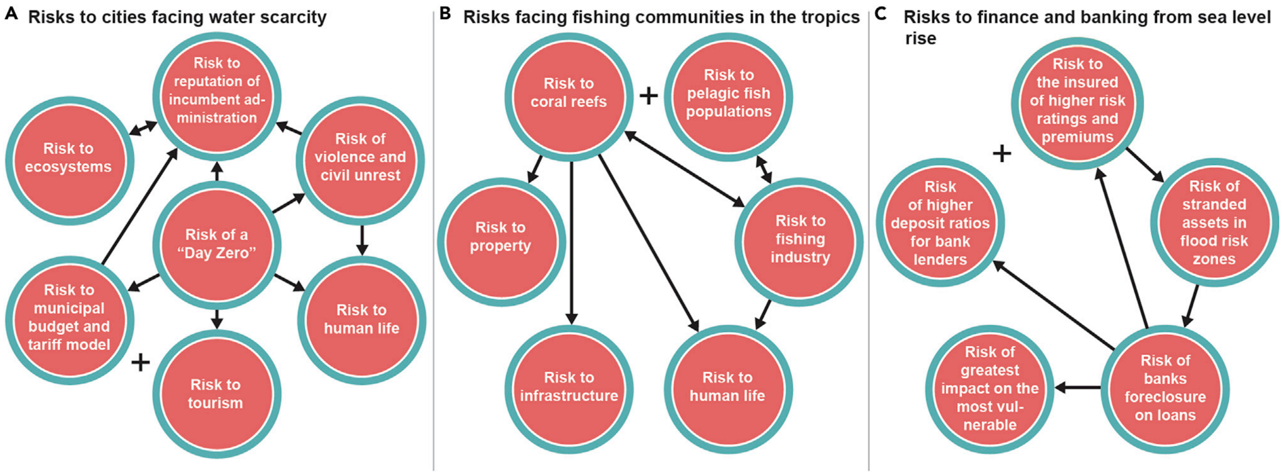

Figure 5. Case studies showing interactions of multiple risks, including compounding and cascading risk interactions, as well as aggregations of risks
Interactions of multiple risks in (A) cities facing water scarcity, (B) fishing communities in the tropics, and (C) finance and banking affected by sea-level rise.

drought, and extreme heat led to severe wildfires that resulted in extensive damage to infrastructure and extended over popular tourist areas, claiming more than 100 lives in the Attica region of Greece.[98] The risk to infrastructure from wildfire was further compounded by ecological responses to the early spring, where increased vegetation growth contributed to faster than normal soil moisture depletion,[100,101] interacting with human responses, including spatial planning and inadequate coordination of evacuation and firefighting measures.[98] In addition to risk to infrastructure from wildfire, vulnerability of infrastructure was determined by the dependency of both energy and transport on available water for electricity generation and shipping, while transport infrastructure was further vulnerable to extreme heat.[98]

Similar category 2 assessments could be undertaken for multiple other sectors, such as agricultural productivity, food security, or food prices.[97] For example, crop loss has been attributed more to drought stress rather than heat stress in this heatwave's compound drought and extreme heat.[102,103] This highlights how interactions of drivers can have different interaction effects. Further, agricultural losses in Northern and Central Europe were partially compensated by a "water seesaw" event among hazards where drought in Northern and Central Europe was correlated with higher rainfall in Southern Europe, such that favorable yield conditions in Southern Europe prevented greater market volatility and price spikes for consumers.[97,100] At the global scale in 2018, a category 2 lens would identify that near-simultaneous heat hazards occurred across Europe, Asia, and North America, leading to an accumulation of risk to food prices globally. However, how these risks to food security interact with other risks,[12] in this case to infrastructure, economic output, and human health, requires a category 3 assessment. The following three cases demonstrate how a category 3 approach builds on and extends category 2 in order to guide actions that reduce negative outcomes from climate change.

Cities facing water scarcity

Urban areas are often where interactions between socio-economic, environmental, and infrastructural systems are revealed during climate extremes, and cities facing water scarcity will increasingly need to manage complex climate change risks. Assessments that consider interacting risks (category 3) are therefore integral to anticipating complex risk and supporting decision making (Figure 5A). For example, the meteorological conditions of the Cape Town Drought (2015–2018) were three times more likely due to anthropogenic greenhouse gas emissions.[104] However, effective responses to the drought were delayed due to the political risk of declaring a disaster and a lack of feasible water supply alternatives.[105] Responses became increasingly urgent in early 2018 as the potential of a "day zero" event became possible, the point at which a city of four million people might run out of water.[106] The risk of day zero was anticipated to cascade to affect risks to health, economic output, and security. A whole-of-society response was called for from public and private actors as the local government's capability to manage the drought response was stretched to its limit.[106] The responses by different groups interacted to generate risks to municipal finance. In particular, as elites invested in private, off-grid water supplies,[105,107] risk of reduced municipal revenue collections from newly off-grid households aggregated with risk of reduced tourism,[106] increasing risk to the reputation of the incumbent administration. The combination of these risks was not considered in planning scenarios prior to the drought. As the city's municipal budget was disrupted, the political risks from capital-intensive responses such as desalination and groundwater abstraction increased and compounded with the ecological risks from proposed water abstraction projects.

In the Cape Town case, building the complexity of risk assessment from category 2 to category 3 has revealed preferred response options. For example, considering interactions among multiple response options for the risk to water supply (in line with category 2) and their interaction across multiple risks (in line with category 3) has led to the inclusion of ecosystem-based adaptation in a new water-sensitive strategy for the city. The clearing of invasive vegetation from catchments is recognized as the most cost-effective way to add water to Cape Town's hydrological system, as well as reducing risk to biodiversity, reducing risk from wildfire, and increasing employment.[108]

Complex climate change risks can lead to a heightened risk of crossing unknown response capacity tipping points.[30] In the run up to day zero, municipal officials developed a Critical Water Shortages Disaster Plan that aimed for responses with street-level specificity, but they faced a lack of detail on cascading risks. When faced with such complex interacting risks, scenario approaches focused on impact cascades[109] or what-if scenario planning can provide a flexible method for assessment of interacting risks and can be deployed relatively rapidly.[53,54,56] Scenario approaches can also be combined with more quantitative stress testing methods to identify where existing climate change adaptation might be insufficient as potential weak points are identified from risk interactions.[110,111] Given deep uncertainty, careful evaluation by a range of experts and stakeholders is a necessary step in this process, and scenario and storyline approaches can be used to engage diverse stakeholders.[56] There must also be sustained co-production of risk assessments among multiple stakeholders that leverages multi-level and polycentric governance approaches to climate change risk.

Fishing communities in the tropics

The maximum catch potential of exploited fish species in tropical regions is projected to decline as a result of climate change by as much as 50% by 2050 relative to 2000–2010 levels.[112] Increased heat stress has already caused widespread coral bleaching,[113] and future warming and acidification are projected to cause a 70%–90% loss of coral if global warming is not held below 1.5°C above pre-industrial levels.[6] These environmental changes are projected to result in fish migration across exclusive economic zones, which creates potential for local and international fisher conflict in the absence of effective governance structures.[76] Caribbean fishing communities illustrate how these risks to tropical corals and fisheries can interact (Figure 5B). As climate change increases risk to pelagic fish catches, small-scale fishers tend to rely on fishing more in shallow waters. This response to declining fish populations can increase risk to coral reefs from switching to fishing techniques that are effective in the short term but damaging to fish populations and corals. Coral reefs act as a natural breakwater, reducing wave energy by an average of 97%.[114] The risk to reefs from maladaptive fishing practices and climate change can cascade to risks to human life, infrastructure, and property on the coastline that is more exposed to waves, storm surges, and coastal erosion during hurricanes.[114] Compounding the risks further, as catches decline, fishers often draw down their assets, reducing their ability to cope with, and rebuild after, hurricanes.[115] Furthermore, damage to coral reefs reduces tourism and associated cash flows, which both provide income diversification but also capital to develop alternative economic activity.[115] Climate change risk to pelagic fisheries therefore has potential to cascade to multiple other risks facing fishing communities in the tropics.

Risk assessment and adaptation strategies that include local and traditional knowledge, and associated sustainable management practices, can help with understanding and addressing complex climate change risks.[116] For example, participatory modeling that informs local communities about the projected severity and timing of multiple climate hazards and co-develops understanding of the local social-ecological systems that integrate multiple risks can better identify response options, as well as the limits of response.[53,64] These approaches can be combined with participatory monitoring in order to regularly update assessments as new interactions of risk drivers or of multiple risks are identified.

In contexts where it is difficult to know or agree on relationships between actions and consequences, then robust decision-making tools using exploratory modeling can be used to pressure test management approaches to myriad plausible interactions of risks to identify robust adaptive strategies into the future.[117] Deep uncertainty analytical methods[117] and systems thinking in simple or modeled form[35,64] can help identify the interacting effects potentially most important to a specific risk analysis.

Finance, banking, and insurance at the coast

As the interacting hazards of sea-level rise, heavy rainfall events, flooding, and land instability compound at the coast, there is a risk to the insured of higher premiums (Figure 5C).[37] This risk can cascade to risk of stranded assets as customers have to choose to either pay higher deductibles to reduce increased premiums, if they can afford to do so, or not hold insurance coverage.[37,118] As a result, they may stay put, abandon assets and move, or rely on disaster relief and recovery funds from the government (taxpayer) as an insurer of last resort. For policy holders, this can create inequities and business risks. If homeowners cannot get insurance, then property values will be depressed. This can cascade to risk of foreclosure on loans from banks, risk of banks having to maintain higher deposit ratios (i.e., lend less), and risk of greatest impact on the most vulnerable who are less able to pay, such as the elderly, low-income residents, or exposed municipalities. Further, climate change risks leave banks exposed because they hold long-term mortgages, often up to 30 years.[37] Managing these diverse risks exposes local government to its own set of risks, since community opposition to coastal hazard management plans can initiate broader opposition to local government strategies and long-term community plans.[119]

Although climate change risk is currently not fully priced into banking and (re)insurance markets, globally there is evidence that the financial services sector is beginning to respond to such risk signals by adopting risk-based pricing for high-intensity rainfall events, sea-level rise, and drought.[37,120] This cannot be done without considering the full breadth of risks and the connections between them.[30] Critical systems thinking and pathways tools can be used to map the interconnections between risks in the finance sector and help reveal where climate change adaptation interventions can be focused. For example, participatory approaches that use expert elicitation and visualize cascading risks as causal diagrams can provide a robust and flexible analytical framework for interacting risks and implications for management.[121] For insurers, this would include fundamental shifts in ways of doing business to include iteratively revised understandings of the probabilities of extreme events.[30] Dynamic adaptive pathways can be employed to help planning and guide responses under deep uncertainty.[122] In such approaches, different response options are considered, including the path dependencies among them through time (e.g., assets that will accumulate behind armored coastlines or the time required to construct major new defenses). This can identify triggers for timely adaptive actions (changes of pathway/behavior) ahead of critical damage thresholds such as increased flooding from sea-level rise,[123] and the points at which new pathways are triggered can be responsive to the difficult-to-quantify outcomes of climate change risk.[122] Co-creation of dynamic adaptive pathways can introduce new framings of risk using simulation games, and involve partnerships among multiple stakeholders in a region that anticipate future interconnections between multiple sectors, including private sector finance, different levels of government, and affected communities.[95,122] Responses based on such methods are usually more resilient and can be done at any scale of assessment,[124] and can be integrated with existing risk screening tools, such as risk registers for climate extremes, infrastructure costs, and finance uncertainties.[26] An integral part of such enhanced assessments is the ability to reflect economic, social, and environmental constraints on resilience. Through identifying how interacting risks affect social equity, interventions can target incremental transformations that enhance resilience capabilities for local communities.[125,126] This enables the interests of a wider range of affected people to be included, leading to more credible, relevant, and lasting resilience.

CONCLUSION

Complex climate change risk assessment is a formidable and urgent challenge. Although real-world experience underscores the importance of interacting drivers of climate change risk and of interactions among multiple risks, these risks have been incompletely and inconsistently assessed to date. The framework provided here seeks to strengthen assessment of complex climate change risks by clarifying the types of interactions that generate risk, and where they originate. Moreover, the integration of responses into the climate change risk framework helps deepen understanding and increases the relevance of climate change risk assessment for a diversity of decision makers, and can help conceptualize risk trade-offs that are being made. Climate change risk assessment may often begin at lower levels of complexity but should be clear about the need to regularly update risk assessments based on new knowledge of interacting risk drivers and interacting risks. As environmental, social, and engineering sciences make joint progress toward these goals, they are beginning to yield more robust risk assessment and inform more detailed decision making to match the complexity of climate change risks.[2,4,37,53] As climate change continues, further development of these new approaches to risk assessment and decision support are increasingly necessary to keep societies safe.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the corresponding authors, Nicholas P. Simpson (nick.simpson@uct.ac.za) and Christopher H. Trisos (christophertrisos@gmail.com).

Materials availability

This study did not generate new unique materials beyond those listed in the supplemental tables.

Data and code availability

This study did not generate or analyze datasets or code.

Methods

Analysis of the IPCC report text was done with NVivo12, exploring where and when types of complex risk and interactions between determinants of risk were used in the three IPCC special reports produced between 2018 and 2019.[5,6,11] These are compared with existing IPCC definitions, where such definitions exist.

After this, an exploratory review of types of complex risk in peer-reviewed literature since 2015, searched for ["climat* change" risk AND "x"] explored each of the following descriptors of interaction linked with risk associated with climate change: impact, effect, risk, hazard, vulnerability, and exposure: aggregate, amplified, cascade, cascading, co-located coinciding, compound, concurrent, correlated, cross effects, cumulative, domino effects, emergent, hyper-, interacting, interconnected, interdependent, multi-, persistent, synchronous, synergistic, systemic, teleconnected, telecoupling. The search began with the first seven pages of Google Scholar and then took a snowball approach exploring the citing articles identified. The search aimed to gain a view on the breadth of the literature and framings of complex risk associated with climate change rather than a systematic review of all published material on each type of complex interaction. Literature highlighted by the team of scholars involved in all three working groups of the IPCC AR6 were also included where remaining gaps or emerging scholarship was identified. The gathered literature was then explored for commonly used definitions and variety of descriptions of complex risk associated with climate change for comparison with use, or lack of use, in IPCC special reports.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.03.005.

ACKNOWLEDGMENTS

This work was carried out with financial support from the UK Government's Foreign, Commonwealth & Development Office and the International Development Research Centre, Ottawa, Canada (grant no. 109419 – 001). C.H.T. was supported by the FLAIR Fellowship Programme: a partnership between the African Academy of Sciences and the Royal Society funded by the UK Government's Global Challenges Research Fund. The authors are grateful to Keren Cooper for her assistance with the development of figures.

DECLARATION OF INTERESTS

A.R. is principal scientist for climate change at the Ministry for the Environment, New Zealand. The opinions expressed in this article do not represent the view or position of the respective employers.

REFERENCES

1. Helbing, D. (2013). Globally networked risks and how to respond. Nature *497*. 51-59. https://doi.org/10.1038/nature12047.
2. Zscheischler, J., Westra, S., van den Hurk, B.J.J.M., Seneviratne, S.I., Ward, P.J., Pitman, A., AghaKouchak, A., Bresch, D.N., Leonard, M., Wahl, T., and Zhang, X. (2018). Future climate risk from compound events. Nat. Clim. Change *8*, 469–477. https://doi.org/10.1038/s41558-018-0156-3.
3. Matthews, T., Wilby, R.L., and Murphy, C. (2019). An emerging tropical cyclone–deadly heat compound hazard. Nat. Clim. Change *9*, 602–606. https://doi.org/10.1038/s41558-019-0525-6.
4. United Nations Office for Disaster Risk Reduction (2019). Global Assessment Report on Disaster Risk Reduction.
5. IPCC (2019). Climate Change and Land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/srccl/.
6. IPCC (2018). Global Warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. https://www.ipcc.ch/sr15/.
7. Correa, D.F., Beyer, H.L., Possingham, H.P., Thomas-Hall, S.R., and Schenk, P.M. (2017). Biodiversity impacts of bioenergy production: microalgae vs. first generation biofuels. Renew. Sustain. Energy Rev. *74*, 1131–1146. https://doi.org/10.1016/j.rser.2017.02.068.

8. Anderson, W.B., Seager, R., Baethgen, W., Cane, M., and You, L. (2019). Synchronous crop failures and climate-forced production variability. Sci. Adv. *5*. eaaw1976. https://doi.org/10.1126/sciadv.aaw1976.

9. Chapman, D., Purse, B.V., Roy, H.E., and Bullock, J.M. (2017). Global trade networks determine the distribution of invasive non-native species. Glob. Ecol. Biogeogr. *26*, 907–917. https://doi.org/10.1111/geb.12599.

10. Gaupp, F. (2020). Extreme events in a globalized food system. One Earth *2*, 518–521. https://doi.org/10.1016/j.oneear.2020.06.001.

11. IPCC (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

12. Harrison, P.A., Dunford, R.W., Holman, I.P., and Rounsevell, M.D.A. (2016). Climate change impact modelling needs to include cross-sectoral interactions. Nat. Clim. Change *6*, 885–890. https://doi.org/10.1038/nclimate3039.

13. Street, R., Di Mauro, M., Humphrey, K., Johns, D., Boyd, E., Crawford-Brown, D., Evans, J., Kitchen, J., Hunt, A., Knox, K., et al. (2017). Cross-cutting issues. In UK Climate Change Risk Assessment Evidence Report (Adaptation Sub-Committee of the Committee on Climate Change), pp. 1–53.

14. Clarke, L., Nichols, L., Vallario, R., Hejazi, M., Horing, J., Janetos, A.C., Mach, K., Mastrandrea, M., Orr, M., Preston, B.L., et al. (2018). Sector interactions, multiple stressors, and complex systems. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, D.R. Reidmiller, C.W. Avery, and D.R. Easterling, et al., eds. (US Global Change Research Program), pp. 638–668.

15. WEF (2020). The Global Risk Report 2020 (World Economic Forum).

16. Lorie, M., Neumann, J.E., Sarofim, M.C., Jones, R., Horton, R.M., Kopp, R.E., Fant, C., Wobus, C., Martinich, J., O'Grady, M., et al. (2020). Modeling coastal flood risk and adaptation response under future climate conditions. Clim. Risk Manag. *29*, 100233. https://doi.org/10.1016/j.crm.2020.100233.

17. Sutton, R.T. (2019). Climate science needs to take risk assessment much more seriously. Bull. Am. Meteorol. Soc. *100*, 1637–1642. https://doi.org/10.1175/bams-d-18-0280.1.

18. Field, C.B., Barros, V., Stocker, T.F., and Dahe, Q. (2012). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (Cambridge University Press).

19. van der Geest, K., de Sherbinin, A., Kienberger, S., Zommers, Z., Sitati, A., Roberts, E., and James, R. (2019). The impacts of climate change on ecosystem services and resulting losses and damages to people and society. In Loss and Damage from Climate Change, R. Mechler, L. Bouwer, T. Schinko, S. Surminski, and L.-B. J, eds. (Springer), pp. 221–236.

20. Leonard, M., Westra, S., Phatak, A., Lambert, M., van den Hurk, B., McInnes, K., Risbey, J., Schuster, S., Jakob, D., and Stafford-Smith, M. (2014). A compound event framework for understanding extreme impacts. Wiley Interdiscip. Rev. Clim. Change *5*, 113–128. https://doi.org/10.1002/wcc.252.

21. Liu, J., Hull, V., Godfray, H.C.J., Tilman, D., Gleick, P., Hoff, H., Pahl-Wostl, C., Xu, Z., Chung, M.G., Sun, J., et al. (2018). Nexus approaches to global sustainable development. Nat. Sustain. *1*, 466–476. https://doi.org/10.1038/s41893-018-0135-8.

22. Rocha, J.C., Peterson, G., Bodin, O., and Levin, S. (2018). Cascading regime shifts within and across scales. Science *362*, 1379–1383. https://doi.org/10.1126/science.aat7850.

23. Atteridge, A., and Remling, E. (2018). Is adaptation reducing vulnerability or redistributing it? Wiley Interdiscip. Rev. Clim. Change *9*. e500. https://doi.org/10.1002/wcc.500.

24. Groves, D.G., Davis, M., Wilkinson, R., and Lempert, R. (2008). Planning for Climate Change in the Inland Empire: Southern California. Water Resources IMPACT *10*, 14–17.

25. Groves, D.G., Bloom, E., Lempert, R.J., Fischbach, J.R., Nevills, J., and Goshi, B. (2015). Developing key indicators for adaptive water planning. J. Water Resour. Plann. Manage. *141*, 7. https://doi.org/10.1061/(asce)wr.1943-5452.0000471.

26. Trindade, B.C., Gold, D.F., Reed, P.M., Zeff, H.B., and Characklis, G.W. (2020). Water pathways: an open source stochastic simulation system for integrated water supply portfolio management and infrastructure investment planning. Environ. Model. Softw. *132*, 104772.

27. IPCC (2019). Annex I: glossary. In Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems, P.R. Shukla, J. Skea, and E.C. Buendia, et al., eds.

28. IPCC (2018). Annex I: glossary. In Global Warming of 15°C: An IPCC Special Report on the Impacts of Global Warming of 15°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, V. Masson-Delmotte, P. Zhai, and H.-O. Pörtner, et al., eds.

29. Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., and Mastrandrea, M.D. (2014). Climate Change 2014 Impacts, Adaptation, and Vulnerability (Cambridge University Press).

30. Raymond, C., Horton, R.M., Zscheischler, J., Martius, O., AghaKouchak, A., Balch, J., Bowen, S.G., Camargo, S.J., Hess, J., Kornhuber, K., et al. (2020). Understanding and managing connected extreme events. Nat. Clim. Change *10*, 611–621. https://doi.org/10.1038/s41558-020-0790-4.

31. Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R.M., van den Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M.D., et al. (2020). A typology of compound weather and climate events. Nat. Rev. Earth Environ. *1*, 333–347. https://doi.org/10.1038/s43017-020-0060-z.

32. Zscheischler, J. (2020). Moving beyond isolated events. Nat. Clim. Change *10*, 583. https://doi.org/10.1038/s41558-020-0846-5.

33. Vogel, M.M., Zscheischler, J., Wartenburger, R., Dee, D., and Seneviratne, S.I. (2019). Concurrent 2018 hot extremes across northern hemisphere due to human-induced climate change. Earths Future *7*, 692–703. https://doi.org/10.1029/2019EF001189.

34. Wahl, T., Jain, S., Bender, J., Meyers, S.D., and Luther, M.E. (2015). Increasing risk of compound flooding from storm surge and rainfall for major US cities. Nat. Clim. Change *5*, 1093–1097. https://doi.org/10.1038/nclimate2736.

35. Bansal, R., and Ochoa, M. (2012). Temperature, aggregate risk, and expected returns (Working Paper 17575).

36. Li, T., Horton, R.M., Bader, D.A., Zhou, M., Liang, X., Ban, J., Sun, Q., and Kinney, P.L. (2016). Aging will amplify the heat-related mortality risk under a changing climate: projection for the elderly in Beijing, China. Sci. Rep. *6*, 28161. https://doi.org/10.1038/srep28161.

37. Lawrence, J., Blackett, P., and Cradock-Henry, N.A. (2020). Cascading climate change impacts and implications. Clim. Risk Manage. *29*, 100234. https://doi.org/10.1016/j.crm.2020.100234.

38. Pescaroli, G., and Alexander, D. (2018). Understanding compound, interconnected, interacting, and cascading risks: a holistic framework. Risk Anal. *38*, 2245–2257. https://doi.org/10.1111/risa.13128.

39. Cavallo, A., and Ireland, V. (2014). Preparing for complex interdependent risks: a system of systems approach to building disaster resilience. Int. J. Disaster Risk Reduction *9*, 181–193. https://doi.org/10.1016/j.ijdrr.2014.05.001.

40. Terzi, S., Torresan, S., Schneiderbauer, S., Critto, A., Zebisch, M., and Marcomini, A. (2019). Multi-risk assessment in mountain regions: a review of modelling approaches for climate change adaptation. J. Environ. Manage *232*, 759–771. https://doi.org/10.1016/j.jenvman.2018.11.100.

41. King, D., Schrag, D., Dadi, Z., Ye, Q., and Ghosh, A. (2017). Climate Change: A Risk Assessment (e Centre for Science and Policy [CSaP] University of Cambridge).

42. Schipper, E.L.F. (2020). Maladaptation: when adaptation to climate change goes very wrong. One Earth *3*, 409–414. https://doi.org/10.1016/j.oneear.2020.09.014.

43. IPCC (2014). Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects. In Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Field, C.B.., V.R. Barros, and D.J. Dokken, et al., eds. (Cambridge University Press), p. 688.

44. Scott, M., Lennon, M., Tubridy, D., Marchman, P., Siders, A.R., Main, K.L., Herrmann, V., Butler, D., Frank, K., Bosomworth, K., et al. (2020). Climate disruption and planning: resistance or retreat? Plann. Theor. Pract. *21*, 125–154. https://doi.org/10.1080/14649357.2020.1704130.

45. Hanna, C., White, I., and Glavovic, B.C. (2021). Managed retreats by whom and how? Identifying and delineating governance modalities. Clim. Risk Manage. *31*, 100278. https://doi.org/10.1016/j.crm.2021.100278.

46. Hillier, J.K., Matthews, T., Wilby, R.L., and Murphy, C. (2020). Multi-hazard dependencies can increase or decrease risk. Nat. Clim. Change *10*, 595–598. https://doi.org/10.1038/s41558-020-0832-y.

47. Raymond, C., Matthews, T., and Horton, R.M. (2020). The emergence of heat and humidity too severe for human tolerance. Sci. Adv. *6*. eaaw1838. https://doi.org/10.1126/sciadv.aaw1838.

48. Mach, K.J., Kraan, C.M., Adger, W.N., Buhaug, H., Burke, M., Fearon, J.D., Field, C.B., Hendrix, C.S., Maystadt, J.-F., O'Loughlin, J., et al. (2019). Climate as a risk factor for armed conflict. Nature *1*, 193–197.

49. USGCRP (2016). Executive summary. In The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment (U.S. Global Change Research Program).

50. Shepherd, T., Jacob, D., Christensen, J.H., Alexander, L., Tegtmeier, S., and Doblas-Reyes, F. (2020). World Climate Research Programme Lighthouse Activity.

51. FutureEarth. (2021). Knowledge-action networks. https://futureearth.org/networks/knowledge-action-networks/for further details.

52. Hallegatte, S., Bangalore, M., Bonzanigo, L., Fay, M., Kane, T., Narloch, U., Rozenberg, J., Treguer, D., and Vogt-Schilb, A. (2016). "Shock Waves" Managing the Impacts of Climate Change on Poverty.

53. Dutra, L.X.C., Bayliss, P., McGregor, S., Christophersen, P., Scheepers, K., Woodward, E., Ligtermoet, E., and Melo, L.F.C. (2018). Understanding climate-change adaptation on Kakadu National Park, using a combined diagnostic and modelling framework: a case study at Yellow Water wetland. Mar. Freshw. Res. *69*, 1146–1158.

54. Bayliss, P., Finlayson, C.M., Innes, J., Norman-López, A., Bartolo, R., Harford, A., Pettit, N.E., Humphrey, C.L., Van Dam, R., Dutra, L.X.C., et al. (2018). An integrated risk-assessment framework for multiple threats to floodplain values in the Kakadu Region, Australia, under a changing climate. Mar. Freshw. Res. *69*, 1159–1185.

55. Beckage, B., Gross, L.J., Lacasse, K., Carr, E., Metcalf, S.S., Winter, J.M., Howe, P.D., Fefferman, N., Franck, T., Zia, A., et al. (2018). Linking models of human behaviour and climate alters projected climate change. Nat. Clim. Change *8*, 79–84. https://doi.org/10.1038/s41558-017-0031-7.

56. Shepherd, T.G., Boyd, E., Calel, R.A., Chapman, S.C., Dessai, S., Dima-West, I.M., Fowler, H.J., James, R., Maraun, D., Martius, O., et al. (2018). Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. Clim. Change *151*, 555–571. https://doi.org/10.1007/s10584-018-2317-9.

57. Surminski, S., and Hudson, P. (2017). Investigating the risk reduction potential of disaster insurance across Europe, the Geneva Papers on risk and insurance - issues and practice *42*, 247–274. https://doi.org/10.1057/s41288-016-0039-7.

58. Weaver, C.P., Moss, R.H., Ebi, K.L., Gleick, P.H., Stern, P.C., Tebaldi, C., Wilson, R.S., and Arvai, J.L. (2017). Corrigendum: 'Reframing climate change assessments around risk: recommendations for the US National Climate Assessment'. Environ. Res. Lett. *12*, 099501. https://doi.org/10.1088/1748-9326/aa846a.

59. Heinrichs, D., Krellenberg, K., and Fragkias, M. (2013). Urban responses to climate change: theories and governance practice in cities of the global South. Int. J. Urban Reg. Res. *37*, 1865–1878. https://doi.org/10.1111/1468-2427.12031.

60. Suarez, P., and van Aalst, M.K. (2017). Geoengineering: a humanitarian concern. Earth's Future *5*, 183–195. https://doi.org/10.1002/2016ef000464.

61. Carlson, C.J., and Trisos, C.H. (2018). Climate engineering needs a clean bill of health. Journal *8*, 843–845. https://doi.org/10.1038/s41558-018-0294-7.

62. Haikola, S., Hansson, A., and Anshelm, J. (2019). From polarization to reluctant acceptance–bioenergy with carbon capture and storage (BECCS) and the post-normalization of the climate debate. J. Integr. Environ. Sci. *16*, 45–69. https://doi.org/10.1080/1943815x.2019.1579740.

63. Trisos, C.H., Alexander, S.M., Gephart, J.A., Gurung, R., McIntyre, P.B., and Short, R.E. (2019). Mosquito net fishing exemplifies conflict among Sustainable Development Goals. Nat. Sustain. *2*, 5–7. https://doi.org/10.1038/s41893-018-0199-5.

64. Hafezi, M., Sahin, O., Stewart, R.A., Connolly, R.M., Mackey, B., and Ware, D. (2020). Adaptation strategies for coral reef ecosystems in Small Island Developing States: integrated modelling of local pressures and long-term climate changes. J. Clean. Prod. *253*, 119864. https://doi.org/10.1016/j.jclepro.2019.119864.

65. Phillips, C.A., Caldas, A., Cleetus, R., Dahl, K.A., Declet-Barreto, J., Licker, R., Merner, L.D., Ortiz-Partida, J.P., Phelan, A.L., Spanger-Siegfried, E., et al. (2020). Compound climate risks in the COVID-19 pandemic. Nat. Clim. Change *10*, 586–588. https://doi.org/10.1038/s41558-020-0804-2.

66. Salas, R.N., Shultz, J.M., and Solomon, C.G. (2020). The climate crisis and covid-19 - a major threat to the pandemic response. N. Engl. J. Med. *383*. e70. https://doi.org/10.1056/NEJMp2022011.

67. FAO (2020). Locust Outbreaks Threaten Food Security in Southern Africa. http://www.fao.org/africa/news/detail-news/en/c/1306167/for further details.

68. GRFC. (2020). Global Report on (Food Crises).

69. Hales, S., de Wet, N., Maindonald, J., and Woodward, A. (2002). Potential effect of population and climate changes on global distribution of dengue fever: an empirical model. Lancet *360*. 830-834. https://doi.org/10.1016/S0140-6736(02)09964-6.

70. Golden, C.D., Allison, E.H., Cheung, W.W., Dey, M.M., Halpern, B.S., McCauley, D.J., Smith, M., Vaitla, B., Zeller, D., and Myers, S.S. (2016). Nutrition: fall in fish catch threatens human health. Nature *534*, 317–320. https://doi.org/10.1038/534317a.

71. Mora, C., Spirandelli, D., Franklin, E.C., Lynham, J., Kantar, M.B., Miles, W., Smith, C.Z., Freel, K., Moy, J., Louis, L.V., et al. (2018). Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. Nat. Clim. Change *8*, 1062–1071. https://doi.org/10.1038/s41558-018-0315-6.

72. Trisos, C.H., Merow, C., and Pigot, A.L. (2020). The projected timing of abrupt ecological disruption from climate change. Nature *580*. 496-501. https://doi.org/10.1038/s41586-020-2189-9.

73. Li, Y., Guan, K., Peng, B., Franz, T.E., Wardlow, B., and Pan, M. (2020). Quantifying irrigation cooling benefits to maize yield in the US Midwest. Glob. Chang Biol. *26*, 3065–3078. https://doi.org/10.1111/gcb.15002.

74. Thiery, W., Visser, A.J., Fischer, E.M., Hauser, M., Hirsch, A.L., Lawrence, D.M., Lejeune, Q., Davin, E.L., and Seneviratne, S.I. (2020). Warming of hot extremes alleviated by expanding irrigation. Nat. Commun. *11*, 290. https://doi.org/10.1038/s41467-019-14075-4.

75. Eriksen, S., Schipper, E.L.F., Scoville-Simonds, M., Vincent, K., Adam, H.N., Brooks, N., Harding, B., Khatri, D., Lenaerts, L., Liverman, D., et al. (2021). Adaptation interventions and their effect on vulnerability in developing countries: help, hindrance or irrelevance? World Dev. *141*, 105383. https://doi.org/10.1016/j.worlddev.2020.105383.

76. Pinsky, M.L., Reygondeau, G., Caddell, R., Palacios-Abrantes, J., Spijkers, J., and Cheung, W.W.L. (2018). Preparing ocean governance for species on the move. Science *360*. 1189-1191. https://doi.org/10.1126/science.aat2360.

77. IPCC (2001). TAR Climate Change 2001: Impacts, Adaptation, and Vulnerability. https://www.ipcc.ch/report/ar3/wg2/.

78. Walker, B., Holling, C.S., Carpenter, S., and Kinzig, A. (2004). Resilience, adaptability and transformability in social–ecological systems. Ecol. Soc. *9*, 5.

79. O'Hare, P., White, I., and Connelly, A. (2016). Insurance as maladaptation: resilience and the 'business as usual' paradox. Environ. Plann. C: Government Policy *34*, 1175–1193. https://doi.org/10.1177/0263774x15602022.

80. Spencer, B., Lawler, J., Lowe, C., Thompson, L., Hinckley, T., Kim, S.-H., Bolton, S., Meschke, S., Olden, J., and Voss, J. (2016). Case studies in co-benefits approaches to climate change mitigation and adaptation. J. Environ. Plann. Manage. *60*, 647–667. https://doi.org/10.1080/09640568.2016.1168287.

81. Hennessey, R., Pittman, J., Morand, A., and Douglas, A. (2017). Co-benefits of integrating climate change adaptation and mitigation in the Canadian energy sector. Energy Policy *111*, 214–221. https://doi.org/10.1016/j.enpol.2017.09.025.

82. Biggs, R., Schluter, M., and Schoon, M.L. (2015). Principles for Building Resilience (Cambridge University Press).

83. McPherson, G., Simpson, J.R., Peper, P.J., Maco, S.E., and Xiao, Q. (2005). Municipal forest benefits and costs in five US cities. J. For. *103*, 411–416. https://doi.org/10.1093/jof/103.8.411.

84. Masuda, Y.J., Castro, B., Aggraeni, I., Wolff, N.H., Ebi, K., Garg, T., Game, E.T., Krenz, J., and Spector, J. (2019). How are healthy, working populations affected by increasing temperatures in the tropics? Implications for climate change adaptation policies. Glob. Environ. Change *56*, 29–40. https://doi.org/10.1016/j.gloenvcha.2019.03.005.

85. Lunt, T., Jones, A.W., Mulhern, W.S., Lezaks, D.P.M., and Jahn, M.M. (2016). Vulnerabilities to agricultural production shocks: an extreme, plausible scenario for assessment of risk for the insurance sector. Clim. Risk Manage. *13*, 1–9. https://doi.org/10.1016/j.crm.2016.05.001.

86. Thornton, P.K. (2010). Livestock production: recent trends, future prospects. Philos. Trans. R. Soc. Lond. B Biol. Sci. *365*, 2853–2867. https://doi.org/10.1098/rstb.2010.0134.

87. Peduzzi, P. (2019). The disaster risk, global change, and sustainability nexus. Sustainability *11*, 957. https://doi.org/10.3390/su11040957.

88. Gaupp, F., Hall, J., Mitchell, D., and Dadson, S. (2019). Increasing risks of multiple breadbasket failure under 1.5 and 2 °C global warming. Agric. Syst. *175*, 34–45. https://doi.org/10.1016/j.agsy.2019.05.010.
89. Guégan, J.-F., Ayouba, A., Cappelle, J., and de Thoisy, B. (2020). Forests and emerging infectious diseases: unleashing the beast within. Environ. Res. Lett. *15*, 083007. https://doi.org/10.1088/1748-9326/ab8dd7.
90. AghaKouchak, A., Chiang, F., Huning, L.S., Love, C.A., Mallakpour, I., Mazdiyasni, O., Moftakhari, H., Papalexiou, S.M., Ragno, E., and Sadegh, M. (2020). Climate extremes and compound hazards in a warming world. Annu. Rev. Earth Planet. Sci. *48*, 519–548. https://doi.org/10.1146/annurev-earth-071719-055228.
91. AghaKouchak, A., Huning, L.S., Chiang, F., Sadegh, M., Vahedifard, F., Mazdiyasni, O., Moftakhari, H., and Mallakpour, I. (2018). How do natural hazards cascade to cause disasters? Nature *561*, 458–460. https://doi.org/10.1038/d41586-018-06783-6.
92. Papanikolaou, V., Adamis, D., Mellon, R.C., Prodromitis, G., and Kyriopoulos, J. (2011). Double disaster: mental health of survivors of wildfires and earthquake in a part of Greece. Psychology *02*, 132–137. https://doi.org/10.4236/psych.2011.22021.
93. Cutter, S.L. (2018). Compound, cascading, or complex disasters: what's in a name?, environment. Sci. Policy Sustain. Dev. *60*, 16–25. https://doi.org/10.1080/00139157.2018.1517518.
94. Srivastava, R.K. (2020). Risk profiles of South Asia-urbanization context. In Managing Urbanization, Climate Change and Disasters in South Asia, R.K. Srivastava, ed. (Springer Singapore), pp. 1–21.
95. Lawrence, J., and Haasnoot, M. (2017). What it took to catalyse uptake of dynamic adaptive pathways planning to address climate change uncertainty. Environ. Sci. Policy *68*, 47–57. https://doi.org/10.1016/j.envsci.2016.12.003.
96. Yiou, P., Cattiaux, J., Faranda, D., Kadygrov, N., Jézéquel, A., Naveau, P., Ribes, A., Robin, Y., Thao, S., van Oldenborgh, G.J., et al. (2020). Analyses of the Northern European summer heatwave of 2018. Bull. Am. Meteorol. Soc. *101*. S35-S40. https://doi.org/10.1175/bams-d-19-0170.1.
97. Beillouin, D., Schauberger, B., Bastos, A., Ciais, P., and Makowski, D. (2020). Impact of extreme weather conditions on European crop production in 2018. Philos. Trans. R. Soc. Lond. B Biol. Sci. *375*, 1810. https://doi.org/10.1098/rstb.2019.0510.
98. Efthimiou, N., Psomiadis, E., and Panagos, P. (2020). Fire severity and soil erosion susceptibility mapping using multi-temporal Earth observation data: the case of Mati fatal wildfire in Eastern Attica, Greece. Catena (Amst) *187*, 104320. https://doi.org/10.1016/j.catena.2019.104320.
99. Eurostat (2019). Agriculture, forestry and fishery statistics, E. Cook, ed. https://doi.org/10.2785/798761.
100. Toreti, A., Belward, A., Perez-Dominguez, I., Naumann, G., Luterbacher, J., Cronie, O., Seguini, L., Manfron, G., Lopez-Lozano, R., Baruth, B., et al. (2019). The exceptional 2018 European water seesaw calls for action on adaptation. Earth's Future *7*, 652–663. https://doi.org/10.1029/2019ef001170.
101. Bastos, A., Ciais, P., Friedlingstein, P., Sitch, S., Pongratz, J., Fan, L., Wigneron, J.P., Weber, U., Reichstein, M., Fu, Z., et al. (2020). Direct and seasonal legacy effects of the 2018 heat wave and drought on European ecosystem productivity. Sci. Adv. *6*. eaba2724. https://doi.org/10.1126/sciadv.aba2724.
102. Ribeiro, A.F.S., Russo, A., Gouveia, C.M., Páscoa, P., and Zscheischler, J. (2020). Risk of crop failure due to compound dry and hot extremes estimated with nested copulas. Biogeosciences *17*, 4815–4830. https://doi.org/10.5194/bg-17-4815-2020.
103. Kornhuber, K., Coumou, D., Vogel, E., Lesk, C., Donges, J.F., Lehmann, J., and Horton, R.M. (2019). Amplified Rossby waves enhance risk of concurrent heatwaves in major breadbasket regions. Nat. Clim. Change *10*, 48–53. https://doi.org/10.1038/s41558-019-0637-z.
104. Otto, F.E.L., Wolski, P., Lehner, F., Tebaldi, C., van Oldenborgh, G.J., Hogesteeger, S., Singh, R., Holden, P., Fučkar, N.S., Odoulami, R.C., et al. (2018). Anthropogenic influence on the drivers of the Western Cape drought 2015–2017. Environ. Res. Lett. *13*, 124010. https://doi.org/10.1088/1748-9326/aae9f9.
105. Simpson, N.P., Shearing, C.D., and Dupont, B. (2019). Climate gating: a case study of emerging responses to Anthropocene risks. Clim. Risk Manage. *26*, 100196. https://doi.org/10.1016/j.crm.2019.100196.
106. Simpson, N.P., Simpson, K.J., Shearing, C.D., and Cirolia, L.R. (2019). Municipal finance and resilience lessons for urban infrastructure management: a case study from the Cape Town drought. Int. J. Urban Sustain. Dev. *11*, 257–276. https://doi.org/10.1080/19463138.2019.1642203.
107. Simpson, N.P., Shearing, C.D., and Dupont, B. (2020). Gated adaptation during the Cape Town drought: mentalities, transitions and pathways to partial nodes of water security. Soc. Nat. Resour. *33*, 1041–1049. https://doi.org/10.1080/08941920.2020.1712756.
108. Madonsela, B., Koop, S., Van Leeuwen, K., and Carden, K. (2019). Evaluation of water governance processes required to transition towards water sensitive urban design—an indicator assessment approach for the city of Cape Town. Water *11*, 14. https://doi.org/10.3390/w11020292.
109. Curry, A., and Schultz, W. (2009). Roads less travelled: different methods, different futures. J. Futures Stud. *13*, 35–60.
110. Wilby, R.L., Dawson, C.W., Murphy, C., O'Connor, P., and Hawkins, E. (2014). The statistical DownScaling model - decision centric (SDSM-DC): conceptual basis and applications. Clim. Res. *61*, 259–276. https://doi.org/10.3354/cr01254.
111. Ebi, K.L., Berry, P., Hayes, K., Boyer, C., Sellers, S., Enright, P.M., and Hess, J.J. (2018). Stress testing the capacity of health systems to manage climate change-related shocks and stresses. Int. J. Environ. Res. Public Health *15*, 2370. https://doi.org/10.3390/ijerph15112370.
112. Cheung, W.W., Watson, R., and Pauly, D. (2013). Signature of ocean warming in global fisheries catch. Nature *497*, 365–368. https://doi.org/10.1038/nature12156.
113. Muniz-Castillo, A.I., Rivera-Sosa, A., Chollett, I., Eakin, C.M., Andrade-Gomez, L., McField, M., and Arias-Gonzalez, J.E. (2019). Three decades of heat stress exposure in Caribbean coral reefs: a new regional delineation to enhance conservation. Sci. Rep. *9*, 11013. https://doi.org/10.1038/s41598-019-47307-0.
114. Ferrario, F., Beck, M.W., Storlazzi, C.D., Micheli, F., Shepard, C.C., and Airoldi, L. (2014). The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nat. Commun. *5*, 3794. https://doi.org/10.1038/ncomms4794.
115. Hogarth, J.R., and Wójcik, D. (2016). An evolutionary approach to adaptive capacity assessment: a case study of Whitehouse, Jamaica. J. Rural Stud. *43*, 248–259. https://doi.org/10.1016/j.jrurstud.2015.12.005.
116. Nakashima, D., Krupnik, I., and Rubis, J.T. (2018). Indigenous Knowledge for Climate Change Assessment and Adaptation (Cambridge University Press).
117. Lempert, R.J. (2019). Robust decision making (RDM). In Decision Making under Deep Uncertainty Marchau, V.A.W.J.., W.E. Walker, P.J.T.M. Bloemen, and S.W. Popper, eds. (Springer International Publishing), pp. 23–51.
118. Storey, B., and Noy, I. (2017). Insuring property under climate change. Policy Q. *13*, 4. https://doi.org/10.26686/pq.v13i4.4603.
119. Siders, A.R. (2019). Managed retreat in the United States. One Earth *1*, 216–225. https://doi.org/10.1016/j.oneear.2019.09.008.
120. Simpson, N.P. (2021). Insurance in the Anthropocene: exposure, solvency and manoeuvrability. In Criminology and Climate: Insurance, Finance and the Regulation of Harmscapes, C. Holley, L. Phelan, and C.D. Shearing, eds. (Routledge), pp. 135–152.
121. Cradock-Henry, N.A., Connolly, J., Blackett, P., and Lawrence, J. (2020). Elaborating a systems methodology for cascading climate change impacts and implications. MethodsX *7*, 100893. https://doi.org/10.1016/j.mex.2020.100893.
122. Haasnoot, M., Biesbroek, R., Lawrence, J., Muccione, V., Lempert, R., and Glavovic, B. (2020). Defining the solution space to accelerate climate change adaptation. Reg. Environ. Change *20*, 37, https://doi.org/10.1007/s10113-020-01623-8.
123. Stephens, S.A., Bell, R.G., and Lawrence, J. (2018). Developing signals to trigger adaptation to sea-level rise. Environ. Res. Lett. *13*, 104004. https://doi.org/10.1088/1748-9326/aadf96.
124. Flood, S., Cradock-Henry, N.A., Blackett, P., and Edwards, P. (2018). Adaptive and interactive climate futures: systematic review of 'serious games' for engagement and decision-making. Environ. Res. Lett. *13*, 063005. https://doi.org/10.1088/1748-9326/aac1c6.
125. Pelling, M., O'Brien, K., and Matyas, D. (2014). Adaptation and transformation. Climatic Change *133*, 113–127. https://doi.org/10.1007/s10584-014-1303-0.
126. O'Brien, K., Hayward, B., and Berkes, F. (2009). Rethinking social contracts building resilience in a changing climate. Ecol. Soc. *14*, 2.