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Research priorities for global food security under extreme events

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Summary

Extreme events, such as those caused by climate change, economic or geopolitical shocks, and pest or disease epidemics, threaten global food security. The complexity of causation, as well as the myriad ways that an event, or a sequence of events, creates cascading and systemic impacts, poses significant challenges to food systems research and policy alike. To identify priority food security risks and research opportunities, we asked experts from a range of fields and geographies to describe key threats to global food security over the next two decades, and to suggest key research questions and gaps on this topic. Here we present a prioritization of the major threats to global food security from extreme events, as well as emerging research questions that highlight the conceptual and practical challenges which exist in designing, adopting, and governing resilient food systems. We hope these findings help in directing research funding and resources towards the food system transformations needed to help society tackle major food system risks and food insecurity under extreme events.

Science for Society

Extreme events threaten the food security of many citizens of the world, our friends, families, and communities, with whom we are connected to at home and abroad. We hear about these threats every day in the news, and in many cases such threats appear to be on the rise. For example, we hear about rising heat waves, floods and droughts ravaging agricultural landscapes, we hear about pest outbreaks and diseases threatening production, about financial crises invoking trade barriers, and about conflicts and wars threatening supply chains as well as food security of inhabitants of conflict zones. Our ability to prepare for these events seems limited. This is exacerbated by their complexity: the fact that multiple events can occur at the same time in different places in the world, and that the impacts of events can cascade through our biophysical and social systems. To date most research and policy on extreme events has developed in isolation, with teams working on different solutions to different components of the challenge of improving the resilience of our food systems. In this article we bring together a number of food system experts to share their perspectives on what they think are the top threats posed by extreme events to global food security over the next two decades, and what they think are the top research questions that scientists should be focussing on to help society prepare and respond to them. We find that underpinning many of key threats rest critical and unsolved governance challenges in international relations, and that many of the highest impact research questions require not only improving data and models but directly addressing how society can design and adopt systems of governance for food systems that are resilient to extreme events in the future.

Introduction

Extreme events caused by climate change, economic or geopolitical shocks, and pest or disease epidemics can induce, spread, and prolong food insecurity [1,2]. They do this by reducing farming and fisheries productivity, threatening subsistence, and disrupting food distribution and public service delivery. Extreme events can also drive increases in food prices and volatility, human migration and political instability. These direct and indirect effects lead to reductions in the availability of, and access to, healthy and nutritious food[1–6]. The magnitude, extent, and complexity of the threats posed by extreme events to global food security can further create cascading and systemic impacts [7,8], that are difficult to predict or plan and prepare for.

The complexity of causation, that is the range of hazards and events that may co-occur and the multiple pathways by which hazards can create societal risks through exposures and vulnerabilities, as well as the widespread scientific and political disagreement on the relative efficacy of potential solutions, call for expert elicitation on this topic[9,10]. Such synthesis can help to balance viewpoints, find areas of consensus, identify problems and solutions which current data or models may not be able to resolve with certainty, and ultimately help both researchers and funding agencies best direct their collective energy and resources to help society tackle these major food system risks.

With ongoing crises affecting food systems -- from weather extremes, to COVID-19, to a range of conflicts -- a horizon scan and priority-setting exercise is timely. Exercises like the one we describe here have been applied to a range of complex issues, such as economic risks[11] to linkages between climate change and conflict[12], climate resilience[13], near term climate impacts[10], and conservation[14, 15], but not for extreme events and food security.

Individual groups and organizations typically determine their own priorities and research gaps, with the consequence that important interdisciplinary priorities may be overlooked. The purpose of this work is to bring together a range of experts in an attempt to build consensus on priorities for research and action to mitigate the effects of extreme events on food insecurity. Through it, we hope to identify major threats and research gaps for both knowledge generation, and implementation. Filling such implementation gaps will necessarily require a fuller analysis of trade-offs in policy making, factors influencing adoption of new management practices or technologies, and an assessment of the value of different kinds of knowledge generation, given different capacities for access and utilization across different contexts.

To identify priority food system risks and research opportunities, we surveyed, online and in-person, a group of 69 food system experts (Supplementary Methods) spanning a range of disciplines and subdisciplines, institutional backgrounds (academia, government and/or international institutions, and NGOs), levels of seniority (e.g., students, postdoctoral researchers, and various levels of faculty), and geographic focus (all continents with permanent human habitation) (Supplementary Figs 1-3), on their perceptions of key emerging threats and priority research questions for global food security in the face of extreme events.

Here we present the summary results of this survey, together with a prioritization of these threats and research questions for the wider research, policy, and funding communities. We explore the nature of the threats identified, as well as the types of questions and perceptions of uncertainty (i.e. in terms of resources required, time, existence of baseline data and methods, requirements for collaboration across geographies, fields, organizations). We hope these findings will broadly aid researchers and funders in focusing on food system transformations needed to deal with the impact of extreme events on global food security.

Threat perception

We asked each member of our expert panel to describe a single emerging threat on the horizon — one which they thought would increase global food insecurity in the face of extreme events over the next two decades (the kind of event and threat, e.g., social, biological, political, was left to the discretion of each expert). From 69 submissions, we identified 32 distinct threats, which covered a range of intersecting social, economic, environmental, and geopolitical dimensions. We then asked the experts to rank each threat along two key dimensions—*Impact* (the impact on global food security) and *Probability* (the probability of occurrence)—following the methods of risk perception commonly used in economic forecasting[7]. We conditioned average scores on individuals, to account for some respondents consistently giving higher or lower scores, a common feature in expert surveys[9].

We found several cross-cutting themes emerged from the synthesis of the expert elicitation. The first theme, *Compound events and cascading risks,* encompasses both correlated risk of disasters across space and time, sectors and regions[16], as well as specific pathways by which a single hazard can cause a cascade of impacts across food systems[7], respectively. The second theme, *Vulnerability and adaptive capacity,* involves factors that predispose communities to losses, or diminishes their ability to cope with a loss when it occurs[17]. Finally, *Cooperation/conflict*—itself a key component of vulnerability and adaptive capacity—was identified as a third theme, presenting in both acute or chronic conditions, which can undermine communities' and nations' abilities to resist and respond to extreme events when they occur[18,19]. We explain top ranking threats below, but also include the full list in Supplementary Table 1.

Food system exposure to events of a compound nature has received increasing research attention in recent years[16] (albeit with a climate focus), so it is perhaps little surprise that our panel identified multiple risks which fell into this category. These included key compound events in specific world regions, such as co-occurring heat waves and droughts in Sub-Saharan Africa[20], or combined monsoon and meltwater disruptions in Asia[21,22]. They also included other globally relevant threats, such as sequential exposure to hazards throughout cropping seasons[23] or across major breadbaskets[24,25], and co-occurring heat-waves at land and sea affecting food supplies[26,27]. Physical drivers of these correlated hazards include simple location shifts in temperature distributions across multiple geographies[28], disruptions to atmospheric circulation patterns such as El Niño Southern Oscillation (ENSO) or the North Atlantic Oscillation (NAO)[29], and amplified Rossby Waves[30] as well as the crossing of large-scale tipping points in climate leading to unprecedented weather regimes on a long-term basis[31]. Exposure of food systems to cascading risks was also of increasing concern and included risk of disruption to critical infrastructure, transport, and public utility systems[32], and disruption of choke points in food supply chains impacting multiple processes and actors in food systems simultaneously or in sequence[33].

Like concerns over the changing nature of compound hazards, issues related to vulnerability and adaptive capacity of particular human populations also received attention. Perennial issues, such as increased water demand from population growth—impacting access to clean water, groundwater depletion, and lack of ability to irrigate sustainably—were perceived as top threats that increase vulnerability and reduce adaptive capacity to extreme events[34–36]. Similarly, income reversals for the poor (already happening pre-COVID)[37,38] coupled with price transmissions, especially in import-dependent low and middle-income countries[39,40], were ranked as top threats. Of additional notable concern was an agricultural development trajectory of increasing industrialization leading to a loss of managed diversity on farms (crops and livestock), and concentration of food flows in supply chains and actors[41,42]; as well as biodiversity loss and loss of ecosystem services supporting food and feed for animal and fish populations[43].

Finally, human conflict was identified as a key threat to global food security which could increase over the next two decades. More than 50% of the world's hungry live in conflict regions, and increasing food insecurity within failed states or in regions with political instability, terrorism, civil unrest and/or armed conflict was seen as a key threat to global food security by our panel[2,44]. Of similar concern were migration and displacement, with associated impacts not only on refugee and migrant food security and nutrition[45] but also on international cooperation, with important implications for progress on responding to world hunger[19]—a concern supported by recent independent assessments of climate impacts [10]. Governance failures and geopolitical resource conflict[46], resource grabbing on land and sea by wealthier nations that have depleted their own resource bases[47], increasing polarization of politics within and between countries, and trade barriers affecting trade and disaster aid[3] were all also raised as key threats of concern.

Other top threats included pest and disease outbreaks and marine heatwaves (one of many emerging threats marine systems face)—both poorly understood issues with the potential to affect large cropland or fisheries areas simultaneously and severely. While fall armyworm and locust outbreaks in Sub-Saharan Africa in recent years have received media attention[48], data on pest damage and losses at the field level are poorly documented across the world, with assessments themselves relying on expert elicitation[49] or models built on sparse or coarse resolution data and or simplified assumptions that do not account for the huge diversity of damage functions and interactions between different pests and diseases[50,51]. For marine heatwaves, only a few experts on our team felt qualified to rank its risk level, but those that did ranked this threat highly, with the importance of this issue being supported by a growing literature on this topic[52–54] .

Research priorities

In addition to asking experts their perceptions on key threats to global food security from extreme events, we also asked participants to identify top-priority research questions on the topic of extreme events and food security. We prioritized the initial 179 responses into 50 by asking the panel to rank the submitted questions along dimensions of research impact and difficulty—how impactful they thought answering the question would be (i.e. in terms of helping to ensure food security in the face of extreme events), and how difficult it would be to answer it (i.e., resources required, time, existence of baseline data and methods, requirements for collaboration across geographies, fields, organizations). Using this prioritization, we differentiated research questions into those that were *lower* *effort,* i.e. were high impact research questions but easier to answer from those that were *higher effort,* i.e. high impact but more difficult to tackle. We then grouped the final prioritized questions into three main emergent themes: *Better maps and predictions*, *farm-level interventions,* and *food system transformation*, as we explain below.

Better maps and predictions

The standard basis for identifying risk, forecasting, and responding to the impact of extreme events on food security is high-quality data. Creating better maps and predictions that can inform proactive prevention and timely response before, during and after extreme events is crucial. However, the quality, frequency, and spatial extent of validated on-the-ground data on food security have kept pace with advances in geospatial predictive analytics tools[55]. Currently, the world's foremost standard for classifying acute food insecurity, the Integrated Food Security Phase Classification (IPC), relies heavily on expert judgement[56]. Systemic issues relate to limited funding for 'boots on the ground' and institutionalized survey programs, poor infrastructure and low maturity of data governance systems within key nations[57], as well as limited programs for grassroots participation in data generation and decision-making on acute and chronic food security. This data availability, access, and utilization problem is exacerbated by logistical challenges that *de facto* accompany extreme events, as seen in conflict zones and with the movement restrictions of COVID-19[2,58]. With these critical challenges in mind, which are related to both data generation and the use of data products and services, the lists of questions posed by participants in this category are given below. These questions clearly highlight frontiers for advanced mapping and analytics and modeling of food systems, while at the same time stressing the need to explicitly monitor, update and validate the success of these new technologies and insights for improving food security on the ground. While a few are purely methodological, most are thematic.

Lower effort

1. What are the likely impacts of specific critical infrastructure failures on food security?
2. What is the evidence for cascading impacts from extreme events in developing countries?
3. What types of extreme events affect which types of farmers? [Who is most at risk and what types of adaptive capacity do they need to bolster?]
4. How many individuals are exposed to extreme weather events through hazards which occur in domestic versus export partner countries' production areas?
5. Which import-dependent countries are most vulnerable to climate shocks in major grain exporting countries?

6. To what extent can early warning systems identify and inform people most exposed, vulnerable, and unable to adapt to food insecurity challenges in the face of extreme events?
7. How can big data, artificial intelligence and machine learning best be used to improve early warning systems?
8. How can remote sensing technologies best contribute to reducing food insecurity and better understand increasing extreme events in data-scarce areas?
9. How will flooding affect food production and food systems in developing countries in the future?
10. Where are the hotspots of food production vulnerability to different kinds of extreme events within key producing regions?
11. How do impacts of different kinds of extreme events on agriculture in the sub-Saharan African region vary?
12. Are there tipping points in the intensity of extreme events that will cause global food insufficiency?
13. Is the international food trade system dynamic enough to accommodate compound and cascading events?
14. Which features of early warning systems are essential for them to be effective?
15. What factors drive synchronous or asynchronous crop production, and how are these factors changing in the past and the future?

Higher effort

1. How resilient are different food system sectors to a range of key perturbations? [Can they be stress tested?]
2. To what extent does early warning for high risk pest outbreaks for Africa improve food security on the ground?
3. How will geographies of pests change in the face of climate change?
4. Can we develop globally dynamic predictions of the stocks and flows of food?
5. What methods best predict cascading impacts from extreme events across food systems?
6. How accurate are seasonal-to-annual food security forecasts, and do these forecasts become more accurate by incorporating climate and weather forecasts?
7. Can we build accurate sub-seasonal models of precipitation in Sub-Saharan Africa, and what can and cannot be said with the current network of observational weather station data?
8. What earth system features (e.g. atmosphere, ocean, land surface, and cryosphere) are best at predicting seasonal-scale extremes for key agricultural and populous regions around the globe?
9. How does the frequency and intensity of extreme events and their subsequent impact on global food security (from both land and sea) change under different climate change scenarios and Shared Socio-economic Pathways?
10. Can artificial intelligence be used to predict extreme event probability and risk profiles and the range of possibilities of future extreme event occurrence?

11. How much would a global network of smart farms providing dynamic data (on farm level soil, water, air, crop changes in response to shocks), help to inform risk reduction for different production systems?

Farm-level interventions

A key focal point for research on food security in the face of extreme events is at the farm level. This is because despite being food producers, many of the world's farmers, herders, hunters, and fishers, are themselves food insecure. This brings a double benefit to research focused on enhancing resilience to extreme events at the farm level, and in production systems more generally, not only for global food security through stabilizing supply, but also for improved livelihoods. However, food producers operate in socio-ecological systems that may enable or restrict their ability to be resilient or adapt to extreme events. Even when armed with knowledge of resilience enhancing practices, socioeconomic constraints or incentives can shape vulnerability to extreme events. For example, the presence of well-functioning insurance markets can encourage farmers to plant drought-sensitive crops because of moral hazard (where an actor is incentivized to increase exposure because they do not bear the full costs of that risk)[59] while the absence of financial markets in combination with liquidity constraints can also prevent farmers from investing in resilient agricultural practices[60]. One example of the latter mechanism include slow adoption rates of drought or flood tolerant seed varieties or irrigation systems in many developing countries.

A range of priority research questions are listed below. In addition, similar but adapted questions should be explored for populations involved in non-sedentary agriculture, capture and farming fisheries, or hunting and foraging activities. A key overall theme is on farm-level diversification, which is critical given that the dominant agricultural development trajectory has been away from diversified farming systems and toward reduced biodiversity in farming landscapes.

Lower effort

1. Which on-farm practices increase resilience to drought, are cost-effective and easily adopted?
2. What are the effects of crop diversification on pest, drought, and disease resistance?
3. How much can increasing crop diversity improve smallholders' adaptive capacity?
4. How do intercropping systems based on productive perennial crops & legumes assist in drought tolerant production systems?
5. How does farmer livelihood diversification mediate food insecurity during extreme weather events?
6. How can we best assist food producers in their response to short-term (acute) extreme events (extreme rainfall, high-intensity storms, extreme temperature, storm surge, etc.)?

Higher effort

1. How context dependent are on-farm resilience practices across the world, and are there common themes, interventions and technologies that work across multiple locations?
2. How does the loss of biodiversity make cropping systems more susceptible to extreme events?

Food system transformation

It is widely recognized that system-level interventions are required to address existing structural constraints in food systems[61], without which the benefits of better maps and predictions and improved evidence synthesis of farm-level interventions for addressing food security in the face of extreme events will not be realized. Many groups have discussed the issue of transforming food systems for improved resilience, including the Committee on World Food Security at the UN, IPES-Food, International Assessment of Agricultural Knowledge, Science and Technology for Development, and the UN Food Systems Summit (UNFSS)[62–65]. However, the community currently remains divided on how food system resilience can be increased through the application of specific solutions, with ongoing concerns about the inequitable distribution of power and resources in food systems. The majority of research questions pertaining to this theme were, not surprisingly, deemed more difficult to answer. However, they address many critical issues which, building on the above categories, sit squarely at the intersection of information generation and availability versus utilization of that information for improving food security. As such, understanding ways to close the implementation gap, with a particular focus on governance, roles of different actors, and the key actions required, underscores a key research priority for improving food security under extreme events.

Lower effort

1. How does crop diversification at the household, community, and regional scales mediate food insecurity during extreme climate events?
2. How can food production and supply chains be made robust to disruptions from extreme events affecting multiple regions, or the same region sequentially?
3. What mitigating steps (e.g. Nationally Determined Contributions (NDCs), climate-smart agriculture) will also help provide resilience against extreme events?
4. What is the effect of agroecological management of food systems on farmer vulnerability to extreme events?
5. In what ways does insurance enhance or undermine food security in the face of extreme events?

Higher effort

1. What does governance for resilient food systems look like?
2. What are the major obstacles in developing resilience to extreme events in small-scale farming systems?
3. What are the most effective approaches for enhancing adaptive capacities at local and regional levels?
4. What are the practical tools and policies for the world’s poor within the scope of limited resources, institutions, infrastructure, capacity, to adapt to the extreme events and food insecurity in the near to medium term?
5. What are some feasible policy (top down) or community (bottom up) pathways for different sectors to enhance the resilience of food security to extreme events?
6. What are policies that make farming systems less vulnerable to extreme events, without negatively affecting other sustainable development goals?
7. How does land access affect rural vulnerability to extreme events, and what has been the effect, globally, of land reform efforts on food security and poverty in the face of extreme events?
8. How can international food prices and distribution systems enable widespread food security without lowering food prices so much that they harm local and regional producers?
9. What are the key societal adaptations required to deal with synchronous crop failures?
10. What are the major barriers undermining the effective uptake of adaptation strategies and how can the limitations associated with these barriers be addressed?
11. What are the most cost-effective strategies to reduce the impacts of production shocks on food access for the world's poor?

Outlook

Identifying key priorities for researchers and funders can be greatly aided through crowdsourcing approaches, which collect the knowledge and wisdom of many, and reduce bias associated with any particular researcher or group[66]. While similar exercises have been undertaken across a range of fields and topics, this work presents, as far as we know, the first attempt to build consensus on the major threats and priorities for research on food security in the face of extreme events from experts working with diverse backgrounds and expertise and geographic foci. New panel compositions and teams may provide different perspectives, particularly with higher representation of fisheries, livestock, hunting and foraging expertise. At the same time we recognize that many of the issues we identified are important across these diverse domains. With these points in mind, our results provide some clear insights into some of the major issues threatening global food security from extreme events over the next two decades, as well as examples of some of the top research questions on this topic.

Our analysis found experts perceived threats on correlated risks across geographies and sequential years to be high. While this topic has previously received attention from a climate perspective[16], our analysis extends this further to a broader range of hazards. There was significant concern that compound events will continue to lead to reductions in redundancy, and degrade communities', regions', and nations' abilities to respond to events when they occur. Furthermore, major socio-political, geophysical, and climatological changes in Africa and Asia present key connected and compounding threats to many of the world's most food insecure.

Our prioritization also indicated that both scientists and practitioners have a need for more granular data and better maps, and improved predictive capacity. New methods of analysis and technologies have allowed for improved advisories, surveillance, monitoring, and humanitarian response[67,68], but At the same time a scarcity of ground data and lack of systems for grassroots data governance, as well as the underutilized role of forecasting in decision-making (such as timely disbursement of resources that limit the scale of disasters) limits the potential of these technologies. There is a need to ensure the design of new tools and data and information products is inclusive and coupled with capacity building, improved access and utilization, respect for data sovereignty, and evaluation in terms of ultimate on the ground impact.

Our findings support the notion that the pathway to peace globally remains essential for ensuring global food security in the face of extreme events. Conflict and lack of cooperation--in a variety of manifestations, and at different political scales--continues to present a major impediment to global food security and is a key factor that predisposes communities and nations to disasters following shocks[3,18]. Supporting this consensus, since the inception of this project several serious new conflicts have arisen, from the current Ethiopian civil war to the Ukraine-Russia war, all seriously threatening regional and global food security.

Markets play an important role in moderating the impacts of local shocks[67], through mediating access to resources, incentivizing resilient production practices and spreading risk across geographies. At the same time, markets enhance certain risks which include exposure to risk cascades through interrupted trade and supply chains, price transmission effects for low-income countries, and loss of food sovereignty and redundancy through short-term gains inefficiency in food supplies (including 'just-in-time' contracting). Markets that fail to price the cost of the loss of food system resilience lead to increased systemic risks. Thus, understanding how to better utilize the power of markets while mitigating the risks they bring to food security is critical to minimize the knock-on effects of extreme events when they do occur.

We found that major threat groupings of conflict, compound/cascading events, and vulnerability and adaptive capacity (e.g., water security and poverty eradication[38], biodiversity loss, and the vulnerability these impart to food systems, both on land and sea[43]) emerged from our analysis, which raises two interrelated questions: Why did these themes emerge? And what underpins them? All carry major uncertainty in terms of effective and timely resolution, all also represent cross-border issues and their resolution requires tackling many outstanding problems of international relations. As we have discussed above, this remains a major challenge for conflict, poverty reduction, and for responding to both cascading events and compound events. For example, the reductions in the likelihood of compound extreme weather events depend on the speed at which governments can collectively realize climate targets which itself is uncertain. This uncertainty in action on climate change is in turn exacerbated by war and policy responses, including, concerns around short-term energy security. A key connecting thread is that underpinning all these emergent categories of risks are failures to engender trust and commit to shared values in international relations and governance.

An important question that arose during our discussions as a group concerned the relative value of prioritizing new research questions, when existing information is not being effectively used for ensuring food security. Part of the gap between knowledge generation and use results directly from access and utilization gaps, which themselves represent both hard and soft infrastructure issues, which differentially influence communities' abilities and capacity to access and use information generated by scientists. At the same time, implementation gaps can also exist because of institutional or governance silos, jurisdictional constraints, resource availability constraints, scientific literacy, or political capture by particular actors, which can limit the utilization of information even if it is available and accessible.

Several key research priorities, particularly those from the transformation theme, speak to these issues. We identified questions on enablers of social change, mechanisms for building trust between actors at multiple levels and across contexts, levers for balancing power and equity in food systems, as well as on developing governance frameworks for ensuring resilience to extreme events. How to translate information and knowledge into action is clearly itself a key research priority and represents a large knowledge gap. These research questions are highly complex, demand strong multidisciplinary expertise and approaches, and require new funding efforts and coordination, to assess which kinds of information hold the most value for leveraging change. They also require researchers to step beyond their own silos and place their efforts where they are most needed to enable such transformations.

Extreme events impact global food security through a multitude of pathways. Some of the threats highlighted here are recognized by the panel to be ‘already happening’ or ‘age-old issues’, but are of magnified importance in the next two decades. In contrast, some of the complex linkages between social and natural systems identified here in the context of extreme events are only just beginning to be made by others[69]. There is little doubt that COVID-19 and ongoing and emerging conflicts and wars have shed new light on these kinds of problems. We are all mindful that research and resources in the public and private sectors are not infinite; at the same time, tackling some of the highest impact research questions will require significant investments of time and money. However, these investments are needed, as extreme events will continue to threaten global food security over the near to medium term. As such, we see it as our responsibility, as practitioners and researchers with expertise in this area, to join forces and help address these challenges head-on.

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Supplementary Information

Supplementary Methods

We used a modified version of the Delphi technique[70] to identify threats for extreme events and food security globally. This horizon scanning method has been applied successfully in a similar manner to identify emerging issues for global conservation and biological diversity[14]. We also used expert elicitation and a priority-setting exercise to identify priority research questions for extreme events and food security. This method, or variations of it, have been applied to identify top research questions in a range of research fields and contexts[15].

We surveyed experts on top threats and priority research questions by i) circulating a request to participate within our professional networks with an initial online survey and, following this ii) an in person workshop session on “Extreme Events and Food Security” at the “Extreme Events - Building Climate Resilient Societies” conference, which was funded by the VW Foundation and held 9-11 Nov. 2019 in Hannover, Germany. We asked for open-format text answers to the following question:

“Describe an emerging threat on the horizon, which could increase food insecurity in the face of extreme events over the next two decades.”

Participants were given 100 words to describe one threat and asked to add references and supporting sources. As part of these same initial submission rounds, we also asked participants to identify up to three responses to the question:

“Identify a top priority research question on the topic of extreme events and food security”

In the first round of expert elicitation via the online survey and workshop, we received 69 replies (69 threats, 179 questions) from participants covering a wide range of expertise, institutional background (academia, government or supranational institutions, and NGOs), seniority (Ph.D. students, PostDocs, and various levels of Professors and Lecturers), and geographic focus (all continents were covered, with a particular emphasis on Africa and Asia). This experience can be seen in SI Figs 1-3, which show the details of participants’ area of expertise, years of experience, and geographic research focus as collected on the initial online survey.

During the in-person workshop, we collected all the online and in person submissions and undertook a pilot ranking exercise of the responses. Here we separated the threats and questions into preliminary themes and asked 2-3 experts that self-identified with each theme to review the list, undertake a pilot ranking exercise to test the prioritization methodology, to identify any extensively broad or duplicate questions that should be eliminated and to make any other suggestions.

After the workshop, a moderator removed threats and questions flagged as obvious duplicates or being too broad, and reworded others for clarity, resulting in 32 threats and 147 questions that were sent out to the full group of contributors in a second online survey. We did not remove 'low-quality research questions'[71]. While we recognize this may have resulted in some questions being of perceived higher research quality than others (e.g. having both theoretical and empirical components, sufficient granularity, not being double barrelled), we wished to maintain, as much as possible, the diversity of different ideas and sources submitted for full consultation.

We compiled these revised lists into a second set of online surveys for prioritization. We invited the full list of experts (N = 69), to rank the list of refined threats and research questions, each presented in their own survey, in which items were presented in randomized order per participant, and participants were asked to rank each item (whether a threat of research question) on simple likert scales (high to low; 1 to 5, with non-anchored intervals). For threats, these scales included *Impact* (What is the impact of this threat on global food security?) and *Probability* (What is the probability of this threat occurring?). For research questions, these scales included *Impact* (How much impact do you think the research question will have if answered?), *Difficulty* (What difficulty level does this research question have?), and *Expertise* (What is your level of expertise in the topic area of this question?). In total, we received N=30, and N=29 responses for threat and research question prioritization surveys, respectively. We piloted each survey prior to sending it out to confirm the estimated time for the survey, and to ensure it was navigable and that the FAQ was clear.

We then used hierarchical cumulative link models[72] to estimate the modes of the likert scales, and probabilities of those modes, for each threat and research question, and for each response (e.g. Impact, Probability for threats, and Impact, Difficulty and Expertise for research questions) conditioning on individuals (which were treated as random intercepts). For research questions we also conditioned mode probability estimates on expertise level (treated as fixed intercepts) to account for higher likelihood of individuals giving higher priority for questions related to their own fields. We then ranked each outcome on the concatenation of the mode and probability (e.g. lets say for *Impact* a selection of threats had modes of 5, 5, 4, and probabilities of those modes 0.8, 0.6, 0.9, their concatenation would be 5.08, 5.06, 4.09; and we would rank them in order 1,2,3 from most to least impactful). For identifying top threats (most impactful and highest probability of occurrence) we simply computed the mean rank of *Impact* and *Probability* ranks, and ranked those mean ranks (these ranks are shown in Supplementary Table 1). For identifying top research questions, we identified the top ranking 50 questions in terms of *Impact* and then split them into higher and lower hanging questions based on a simple percentile split in ranks of *Difficulty*.

We then collated the final threats and research questions into emergent themes post prioritization and added examples into a first manuscript draft. We shared this manuscript draft with the full list of contributing experts (N=69) for review and allowed experts to submit suggestions and thoughts, as well as textual edits to the final lists.

Supplementary Figures

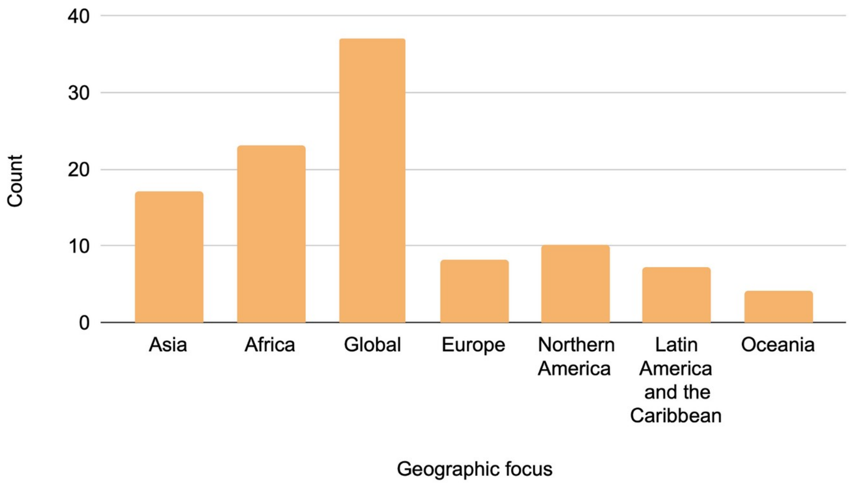

Fig S1 Geographic expertise of experts contributing to the study. Note, experts were allowed to declare more than one focal geography. These data were collected in the initial online survey (see Supplementary Methods).

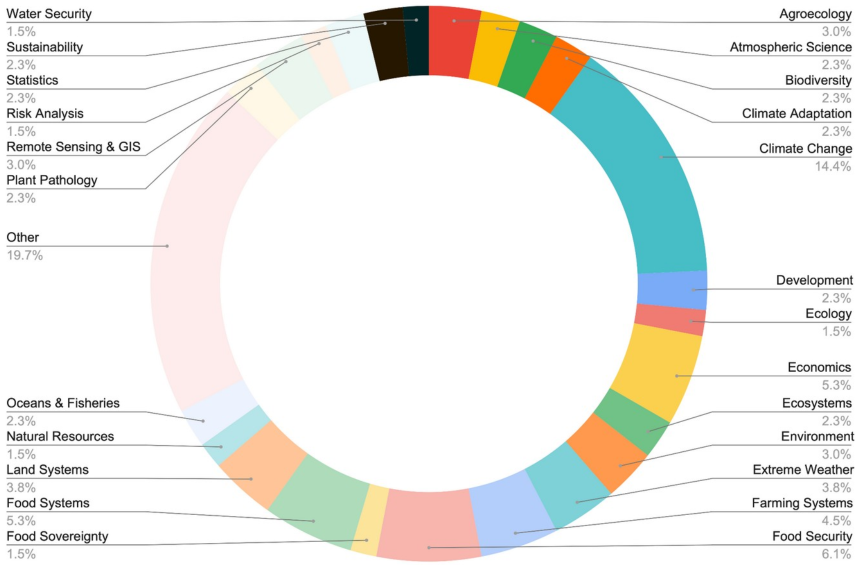

Fig S2 Field of expertise from experts contributing to the study. Note, these were self declared, and some experts declared more than one area of expertise. “Other” includes a range of of additional experts foci not shown, in philosophy, ethics, rural sociology, conflict science, humanitarian response, plant genomics, livestock systems, crop modeling, coastal hazards, environmental monitoring, drought management, urban food systems, gender analysis, landscape ecology, phytosanitation, human nutrition, socio-ecological systems, enterprise management, research performance evaluation, and impact assessment. These data were collected in the initial online survey (see Supplementary Methods).

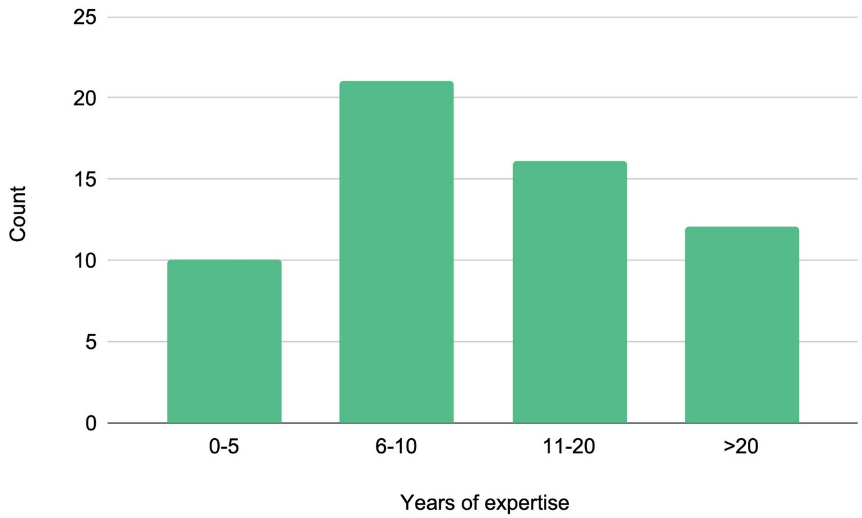

Fig S3 Years of expertise in the declared field from experts contributing to the study. These data were collected in the initial online survey (see Supplementary Methods).

Supplementary Tables

SI Table 1. List of threats ranked and prioritized in this study. See main text for additional context and discussion.

Title	Class	Text	Rank (Impact)	Rank (Probability)	Mean Rank
Increased water demand	Vulnerability/ adaptive capacity	Combination of rising water demand as well as low innovation in ways of growing food with limited amounts of water, will lead to further water insecurity in the face of climate extremes, particularly in irrigation dependent production systems, which will be amplified by population growth, urbanization, and the over-reliance on non-renewable resources, especially groundwater.	1	2	1.5
Drought & heat waves in SSA	Compound events	Losses to crop production by droughts and heat waves in Sub-Saharan Africa resulting in significant increases in food insecurity in the region.	2	1	1.5
Collapse of ecosystem services	Vulnerability/ adaptive capacity	The co-occurrence of extreme events, biodiversity loss, and ecosystem service collapse with negative effects on food production, food prices, and ultimately food security, through loss of essential services such as water regulation, pollination and pest control, and supporting food and feed for fish and animal populations.	4	6	5
Marine heat waves	Other	Heat waves and other extreme events negatively impacting marine resources through changes in their abundance and distribution, especially impacting coastal systems, and dependent communities in small and low income countries.	3	8	5.5
Income inequality	Vulnerability/ adaptive capacity	Production losses and associated price spikes not accompanied by rapid income growth for the poor putting the most vulnerable communities at even greater risk to food insecurity through increased poverty limited access.	12	3	7.5
Political instability and migration	Co-operation/ conflict	Extremes events amplifiying food insecurity from, as well as increasing, conflict, terrorism, and migration/displacement within and between nations.	11	4	7.5
Pest and disease outbreaks	Other	More frequent and severe weather, combined with long term climate change impacts on novel pest distriutions, will lead to increasing pest pressure, more severe outbreaks, and a breakdown in genetic resistance, which will result in significant	10	7	8.5

Title	Class	Text	Rank (Impact)	Rank (Probability)	Mean Rank
		crop losses and health threats for humans and animals.			
Monsoon & meltwater disruption in Asia	Compound events	Major disruptions of monsoon patterns and alterations of meltwater flow patterns in major river basins negatively affecting agricultural production due to missing irrigation water in Asia, and impeding food security for billions dependent on these water resources.	8	10	9
Price shocks and volatility	Vulnerability/ adaptive capacity	Extreme events inducing global food price shocks, which will affect middle and low income countries the most. The strong global market integration of these countries make them vulnerable for price fluctuations transmitted to their local markets and oftentimes these countries lack the capacity to protect their local markets (e.g. because of trade agreements, lack of storage facilities).	14	5	9.5
Low agricultural diversity	Vulnerability/ adaptive capacity	An increasing simplification of global agricultural systems through monoculture cropping and livestock genetics, will make these systems highly dependent on agrochemical inputs and more vulnerable to a range of climatic risks, evolution of pesticide resistance, fuel price volatility, and epidemics.	16	9	12.5
Climate tipping points	Compound events	The crossing of large-scale tipping points in climate will lead to fundamentally different climate regimes and unprecedented weather regimes on a long-term basis. Exceeding those tipping points will have also negative feedback effects by accelerating and intensifying climate change and extreme weather events.	5	20	12.5
Adaptive tipping points	Compound events	An increase in extreme events frequency and severity leading to continued and time compounded losses to agricultural productivity across sequential cropping cycles, exacerbating and accelerating impacts of individual events, and reducing farm level resiliency and adaptive capacity.	13	17	15
Unpredictable weather changes	Other	Major shifts in weather patterns such as storms and rainfall and temperature extremes disproportionally affecting rural communities. Aggravated by changes in	17	14	15.5

Title	Class	Text	Rank (Impact)	Rank (Probability)	Mean Rank
		climate teleconnection patterns, rendering existing agricultural knowledge of seasonality less useful.			
Compound heat waves on land	Compound events	Compound heat waves in space and/or time will aggravate individual heat-related impacts on food production. Simultaneous production shocks from multiple heat waves across agricultural regions have the potential to increase global food prices and food insecurity.	9	24	16.5
Breadbasket failure	Compound events	Multiple breadbasket failures, resulting from co-occuring climate extreme events, pests, and diseases as well as the lack of buffering capacity of global markets, will lead to long-term stability of food and nutrient provisioning.	7	26	16.5
Breeding failures	Vulnerability/ adaptive capacity	Difficulties to breed tolerance to heat stress because of physiological constraints and because the interaction of genetics and environmental factors on plant responses under extremely high temperatures is largely unknown.	23	12	17.5
Compound heat waves on land and sea	Compound events	Co-occurring heat waves on land and sea as the result of shifting mean climates and higher probability of extreme land and sea temperatures leading to both loss of crop yields and available fish catch, leading to a double whammy of food supply shortages.	6	29	17.5
Resource conflict	Co-operation/ conflict	Resource grabbing on land and sea by powerful countries that have exploited their own resource base, and governance failures to control this activity, amplifying the impact of extreme events for the most vulnerable by reducing their capacity to grow, hunt, or access food.	25	11	18
Trade barriers	Co-operation/ conflict	The increasing number and strength of trade barriers by many industrialized and BRIC countries affecting both open trade and disaster aid needed for resilience to shocks to major breadbaskets failures due to extreme events.	21	15	18
Increase in civil unrest	Co-operation/ conflict	Production losses and reduced resource bases and rising food prices as the result of extreme events increasing riots, civil unrest and armed conflict, especially in failed/unstable states.	18	19	18.5
Loss of subsistence capacity	Vulnerability/ adaptive capacity	The interplay between the scale transition to less farmers operating larger farms and reduction in subsistence farming, with increased market dependency for food, will lead to high exposure and food insecurity in the face of extreme events, especially for	26	13	19.5

Title	Class	Text	Rank (Impact)	Rank (Probability)	Mean Rank
		underprivileged and poorer communities.			
Loss of food sovereignty	Vulnerability/ adaptive capacity	The continued rise in corporate control of the food system and the inability to institutionalize and enforce The Right to Food will severely affect the livelihoods of low-income communities and hinder their access to healthy food in the face of extreme events.	24	16	20
Critical infrastructure disruption	Compound events	Damage to critical infrastructure and public utility systems, leaving millions of households affected by minor inconveniences (such as power outages of short duration) to more severe disruptions (such as extended loss of utilities and public services for days and weeks, and the long-term shut-down of bridges, roads, and other transportation networks), with significant disruptive impacts on food insecurity.	19	23	21
Multiple supply chain failures	Compound events	The correlated risk of extreme events throughout supply chains leading to simultaneous stressors on the production, stocking, transport, storage, and retail components of agricultural systems. This is particularly problematic if 'choke points' are affected.	15	30	22.5
Climate skepticism	Co-operation/ conflict	An increase in climate skepticism hindering timely and effective implementation of adaption and mitigation strategies.	20	25	22.5
Workforce heat stress	Other	Extreme heat and other climatic factors having adverse health impacts on farmers and crop workers, and negatively impacting food security both through productivity losses, and for the workers themselves through income loss or health detriments (e.g. from heat exposure or nocturnal working hours) .	32	18	25
Loss of human co-operation	Co-operation/ conflict	Further polarization of politics across a range of scales will lead to increasingly competitive rather than collaborative forms of governance between communities and countries, undermining co-operation at different levels in society.	22	28	25
Ageing farming populations	Vulnerability/ adaptive capacity	A growing age of farmers in agriculture and the lack of successors from younger generations creating severe difficulties for adaption to extreme events.	29	22	25.5
Agricultural intensification	Vulnerability/ adaptive capacity	Global trends of intensifying agricultural systems by conventional means (i.e. optimized for increased yields and calories) further increasing their susceptibility to climate extreme events.	31	21	26

Title	Class	Text	Rank (Impact)	Rank (Probability)	Mean Rank
Increased gender inequality	Vulnerability/ adaptive capacity	Extreme events leading to exacerbation of existing gender inequality, which will entail substantial negative impacts for food security given womens key roles in agricultural production, and food provision within households.	28	27	27.5
Destabilization of pollution sources	Compound events	Threats from nuclear or other major industrial/pollution sources that are susceptible to extreme events severely damaging terrestrial, marine, and other aquatic resources simultaneously.	27	32	29.5
Increasing uncertainty and business risks associated with extreme events will lead to a lack of investment in agriculture, with negative consequences for the creation of globally sustainable and resilient food systems	Vulnerability/ adaptive capacity	Diminished agricultural investments resulting in negative consequences for the creation of globally sustainable and resilient food systems.	30	31	30.5