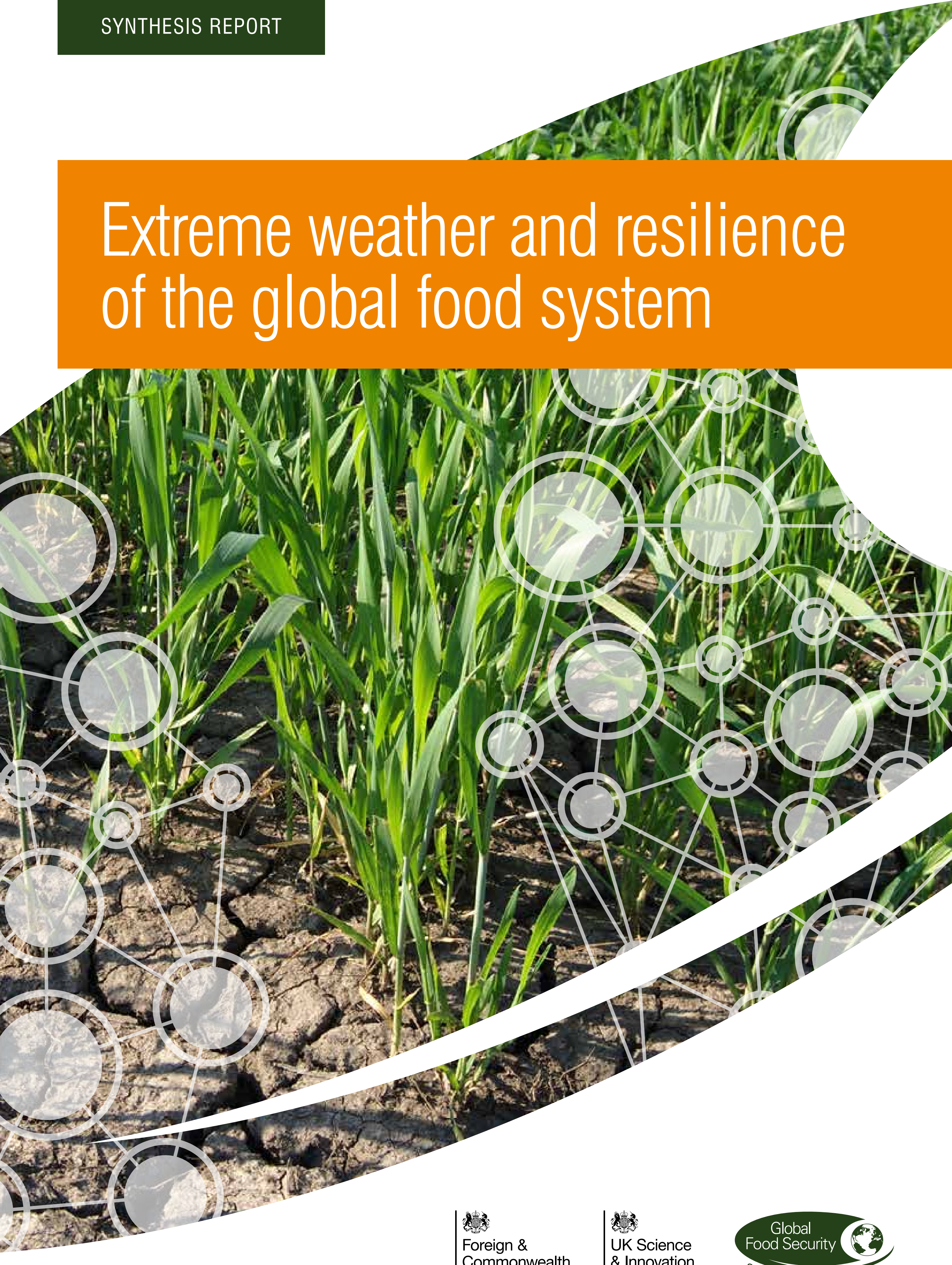
SYNTHESIS REPORT

Extreme weather and resilience of the global food system



Foreign & Commonwealth Office

UK Science & Innovation Network

Global Food Security
Sustainable, healthy food for all

This report originates from a Taskforce of academics, industry and policy experts to examine the resilience of the global food system to extreme weather events. The Taskforce was brought together by the UK's Global Food Security programme and was jointly commissioned by the UK Foreign and Commonwealth Office and UK Government Science and Innovation Network. This Synthesis report on *Extreme weather and resilience of the global food system*, sits in the context of three detailed sub reports on *Climate and global production shocks, Review of the responses to food production shocks* and *Country level impacts of Global Production Shocks*. There is also an overall Extreme weather and resilience of the global food system summary report. The contents of these reports are based upon workshop discussions held at Willis Tower, Chicago in October 2014 and the Foreign and Commonwealth Office, London in February 2015 (see Appendix for a full list).

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Electronic versions of the report series may be found at the addresses below:

Extreme weather and resilience of the global food system summary report
www.foodsecurity.ac.uk/assets/pdfs/extreme-weather-resilience-of-global-food-system.pdf

Climate and Global Crop Production Shocks
www.foodsecurity.ac.uk/assets/pdfs/climate-and-global-crop-production-shocks.pdf

Review of the responses to food production shocks
www.foodsecurity.ac.uk/assets/pdfs/review-of-responses-to-food-production-shocks.pdf

Country level impacts of Global Production Shocks
www.foodsecurity.ac.uk/assets/pdfs/country-impacts-of-global-grain-production-shocks.pdf

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Foreword

Sir David King

UK Foreign Secretary's Special Representative for Climate Change and former UK Government Chief Scientist

This report makes a vital contribution to the study of the risks facing the international food system and helpfully identifies areas where more work is needed.

We know that the climate is changing and weather records are being broken all the time. Some of these weather records make a big impact on people – their ability to make a living and feed their families and in some cases their vulnerability to extreme events.

Looking ahead, we can see that the world is changing, but we are not yet in a position to understand in detail what the weather will look like, and what the events will be that impact upon people's lives the most.

The food system we increasingly rely on is a global enterprise. Up to now it's been pretty robust and extreme weather has had limited impact on a global scale. But if the risks of an event are growing, and it could be unprecedented in scale and extent, how well prepared are we? Especially in the context of an international food system that over time has become increasingly efficient and therefore less resilient, the risks are serious and should be a cause for concern.

Given the potentially huge impacts such an event could have in our increasingly interconnected world, we should be looking carefully at even very low probability situations and the likelihood of the scenarios suggested in this report are far too significant to ignore.

This report examines some of the things we know and identifies areas where we need to know more. It imagines a plausible worst case scenario for the near future, and uses this to look at responses and impacts. It is useful in making us think about ensuring that when such events happen we take timely steps that make the situation better and not worse as well as what we can do now to prepare.

Executive summary

A Taskforce of academics, industry and policy experts was commissioned to examine the resilience of the global food system to extreme weather. This summary is built on three detailed reports: *Climate and global production shocks* (Annex A), *Review of the responses to production shocks* (Annex B) and the *Country-level impacts of global grain production shocks* (Annex C).

We present evidence that the global food system is vulnerable to production shocks caused by extreme weather, and that this risk is growing. Although much more work needs to be done to reduce uncertainty, preliminary analysis of limited existing data suggests that the risk of a 1-in-100 year production shock is likely to increase to 1-in-30 or more by 2040. Additionally, recent studies suggest that our reliance on increasing volumes of global trade, whilst having many benefits, also creates structural vulnerability via a liability to amplify production shocks in some circumstances. Action is therefore needed to improve the resilience of the global food system to weather-related shocks, to mitigate their impact on people. A visual of the scenarios in the report can be found on pages 12-13. Key recommendations include:

Understand the risks better

More research is needed to understand and quantify the risks set out in this report. Our assessment is that they are non-trivial and increasing, but our knowledge of how extreme weather may be connected across the world, and hence the precise probability of multiple bread basket failures, is limited by available model simulations. Modelling limitations also constrain our ability to understand how production shocks translate into short run price impacts.

Explore opportunities for coordinated risk management

As knowledge emerges regarding plausible worst case scenarios, it will be possible for governments, international institutions and businesses to develop contingency plans and establish early warning systems with agreed response protocols. Other opportunities include coordinated management of emergency and/or strategic reserves.

Improve the functioning of international markets

History demonstrates that the actions of market participants in response to production losses, or the behaviours of other actors, are a crucial determinant of price impacts. Other problems that can exacerbate price spikes include low levels of stocks relative to consumption, poor transparency of market information and physical limitations on trade such as infrastructural constraints.

Bolster national resilience to market shocks

Governments should also consider policies to bolster national resilience to international market shocks. This is a particularly important policy agenda for import dependent developing countries with high numbers of poor food consumers, and/or high risk of political instability. The precise mix of appropriate policy measures will vary according to national context.

Adapt agriculture for a changing climate

Agriculture faces a triple challenge. Productivity must be increased by reversing declines in yield growth and closing the gap between actual and attainable yields in the developing world, whilst also reducing its environmental impact (eg 50:1 degradation, depletion of freshwater supplies, increasing greenhouse gas emissions or eutrophication). However, given the increasing risk of extreme weather, this cannot come at the expense of production resilience. Increases in productivity, sustainability and resilience to climate change are required. This will require significant investment from the public and private sectors, as well as new cross-sector collaborations.

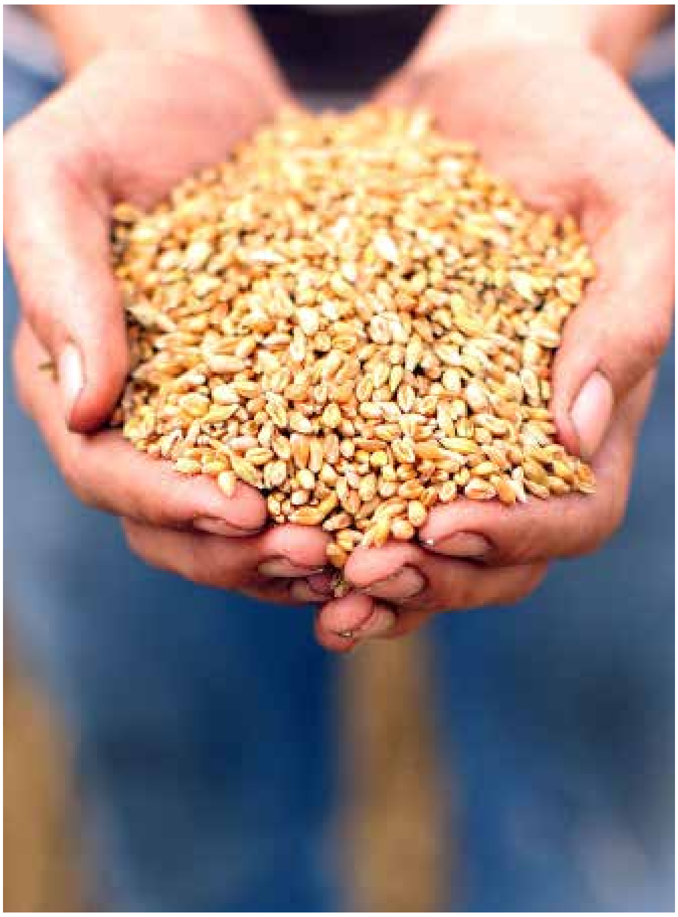
1. Food demand and supply and the impact of weather in a changing world

By 2050, the FAO estimates that demand for food will increase over 60% above the current situation. Demand growth is driven by population and demographic change, and increasing global wealth. This, in turn, leads to greater per capita food demand, often associated with demand for more livestock produce. In 2007/8, a small weather-related production shock, coupled with historically low stock-to-use levels, led to rapid food price inflation, as measured by the FAO Food Price Index and associated with the main internationally traded grains[1]. This increase was compounded by some countries imposing barriers to local export, to ensure their own food security, leading to an FAO price spike of over 100%. A similar price spike occurred in 2010/11, partly influenced by weather in Eastern Europe and Russia[2].

These spikes created a number of significant impacts around the world. In rich countries, where food is freely available, food price inflation was significant and the poorest suffered, resulting in people trading down on food quality or quantity, and in the process spending significantly more. In poorer countries, especially those with fragile governance, rapid food price inflation undermined civil order, and, in part was a spark for the Arab Spring and the consequences that have followed[3]. In 2012, the worst drought to hit the American Midwest for half a century triggered comparable spikes in international maize and soybean prices. This sequence of price spikes, and their consequences, re-alerted the world to the need to focus on global food availability and the volatility in its supply. Sir John Beddington's powerful analogy of "the perfect storm" - of rising demand for food, water and energy whilst climate change creates increasing constraints - became a call to action on how to manage demand growth in a world under pressure.

There is now very extensive and convincing evidence that the climate[4] is changing[5]. Climate change can lead to a change in the mean (average) of a climatic variable, like temperature or rainfall, and/or its variability[6]. Changes in variability are just as important as changes in the average. To caricature this, climate change may result, on average, in an area getting wetter; however, if the variance is also increasing, it is possible for both floods and droughts to become more common. As extreme weather is often associated with the highest impacts on human systems, understanding exactly how the shape of the distribution of weather will change relative to the mean is important[7]. Whilst there is currently incomplete understanding of how extremes will change (see discussion in Annex A), there is nonetheless good evidence that extreme weather events, from intense storms to droughts and heatwaves, are increasing in frequency and severity at a considerable rate[8].

Most agriculture is climate dependent. Weather's variability determines the relative productivity of the seasons[9], and thus underpins variation in global food markets and determines the spatial distribution of agriculture. If production variability is also being driven by increasing variability of the weather across years, it implies there will be increased within-season price instability coupled with longer term challenges to the structure of the food system. The impact of changing patterns of extreme weather on global food system resilience therefore requires more investigation.



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It is easier to make inferences from climate models and historical data about the average climate than it is about the extremes of the distribution, because by their very nature these events are rare, so sample sizes are small. Inferences about extremes are therefore much more uncertain. So, whilst climate models give us a good understanding of how climate may change in future, our understanding of the way extreme events may change is much less certain. For example, the authors of a recent paper[10] comparing data to model predictions of extreme rainfall, concluded: "Our results also show that the global climate models we used may have underestimated the observed trend, which implies that extreme precipitation events may strengthen more quickly in the future than projected and that they may have more severe impacts than estimated." In addition, for some climate phenomena (such as the way that large scale circulation patterns like the southern oscillation may change), inter-model comparison shows considerable variability[11]. Given that "it is difficult to rank models for their accuracy, ...any model integration can be considered equally valid, and those that indicate [worse] conditions imply a future potential risk"[12]. In other words the rarest conditions are the most uncertain and difficult to study, but because they are also typically the most impactful, their study is most important.

2. The US-UK Taskforce on extreme weather & global food system resilience

In 2012, Sir John Beddington, then UK Government Chief Scientific Advisor, commissioned a report on food system resilience from the UK's Food Research Partnership. That report[13] concluded:

> *The complexity of interactions between the global food supply chain and global weather means that the impacts of a particular weather event will vary with the location, timing and the overall context. The evidence is not available properly to describe with any certainty how variable weather will impact on food production systems and worldwide trade, but our contention is that we need greater investigation of what they could be, with perhaps greater consideration being given to reasonable "worst case scenarios". …*
> *The weather in 2012 (drought to floods in the UK, drought, heatwave, floods across the rest of the Northern Hemisphere) cautions us to consider fully that weather may simultaneously impact in different places separated widely in space, and that therefore there is potential for widespread impacts on food supply. Given that the frequency of weather extremes is increasing, the potential for large impacts, and unprecedented ones, is growing.*

In 2014, the UK Foreign and Commonwealth Office and the UK Government Science and Innovation Network (supported also by the Department for the Environment, Food and Rural Affairs) jointly commissioned the UK's Global Food Security programme to bring together a cross-disciplinary UK-US taskforce of experts (see Appendix A) to examine the risks of extreme weather's impact on the food system, the responses the market and policy actors may make to any shortfall in production, and the impacts this may lead to (Figure 1). Given better understanding of climatic risks, likely responses and impacts, a further aim was to highlight positive actions to reduce impacts on people and markets. The Taskforce's work also highlights gaps in our understanding and where further research is needed.

This report summarises the outputs from the Taskforce into three areas: (i) how the changing weather may create shocks to the global food system (Section 3, Annex A), and, from this the development of a "plausible" worst case scenario for a shock; (ii) plausible market and policy responses to the worst case scenario (Section 4, Annex B); and (iii) how the combination of scenario and responses may impact upon different societies, economies and the environment (Section 5, Annex C).

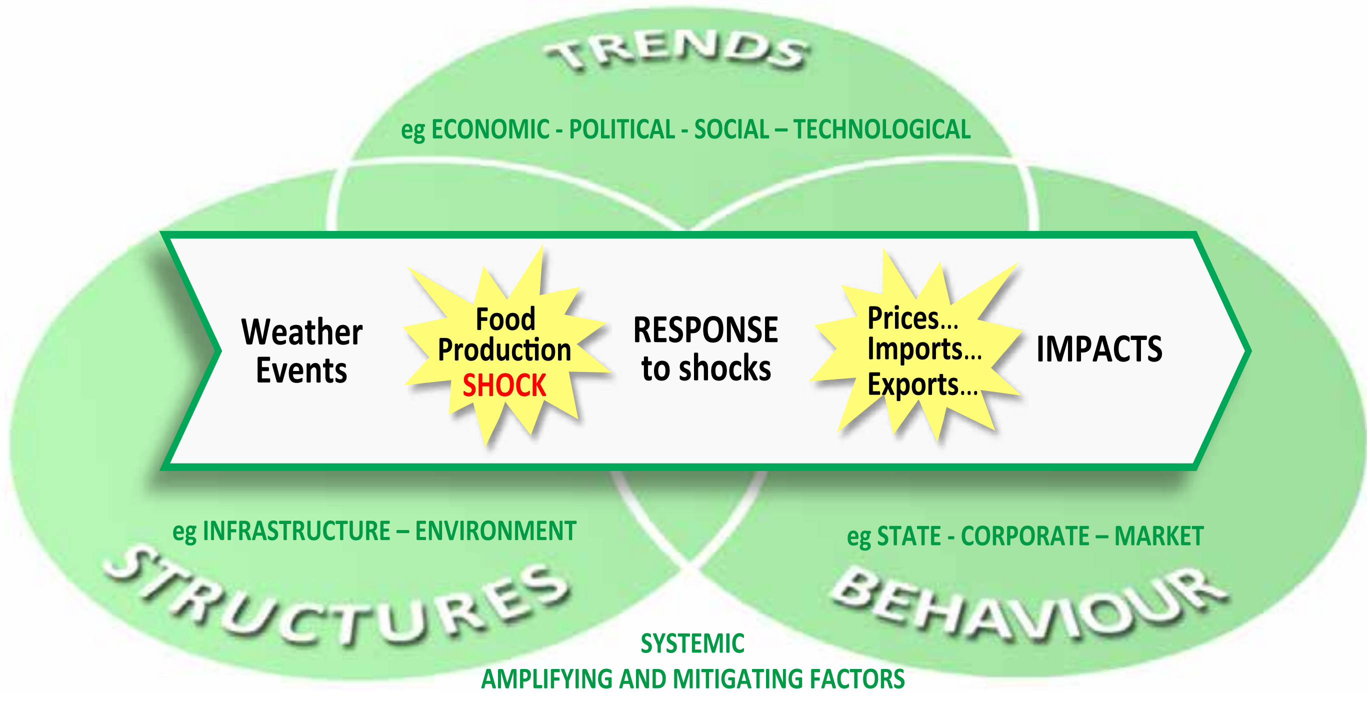

Figure 1: The conceptual framework for devising and assessing different scenarios of disruption to the food supply chain. Analysis was fixed around the two quantitative reference points of a shock to production (in terms of total loss), and the effects on food prices, imports and exports. The disruption pathways described how (a) climatological conditions that could create the shocks (e.g. droughts, storms) and their likelihood, (b) the most plausible and likely policy and market responses to the shock, and (c) the pathways that will result in the global food security impacts.

3. Weather and shocks to the global food system

Food production of the globally most important commodity crops (maize, soybean, wheat and rice) comes from a small number of major producing countries. The exposure of a large proportion of global production of the major crops is therefore concentrated in particular parts of the globe (Figure 2), and so extreme weather events in these regions have the largest impact on global food production. Simultaneous extreme weather events in two or more of these regions – creating a multiple bread basket failure – would represent a serious production shock, however understanding the covariance of extreme weather events in different production regions is currently under-researched. There is an urgent need to understand the driving dynamics of meteorological teleconnections, such as the El Niño – which may be becoming more extreme - in order to quantify the likelihoods of coincident production shocks in major food-producing regions.

By examining production shocks in the recent past, we show that weather events, particularly drought, are a major driver of these shocks. Using the example of these past events we generated a set of scenarios, in the present or near-future, of weather-driven production shocks for each of the four crops (Annex A). These we combined to create a plausible worst case scenario (Box 1).

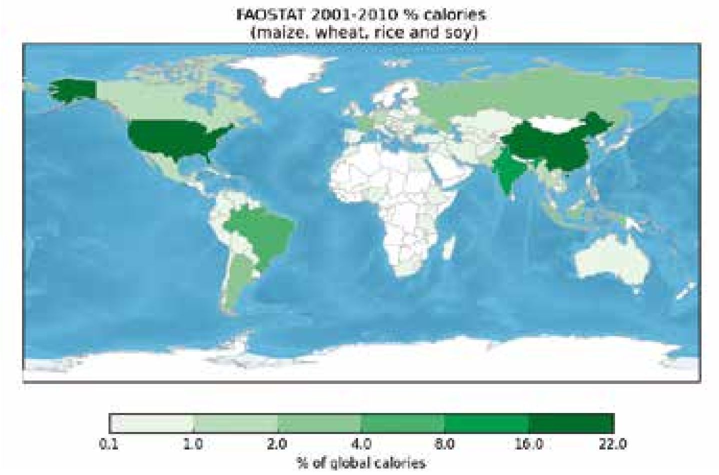

Figure 2. Proportion of the total calories coming from the main four commodity crops per country. Within each country, agricultural production is also typically concentrated (see fig S7a in Foley 2011 for a spatially resolved map). For example, the bulk of calories produced in the US come from soy and maize in the Midwest, in Brazil agricultural production, mainly soy, is concentrated inland from the SE coast; rice predominantly comes from the Indo-Gangetic plain, SE China and SE Asia) and wheat production is concentrated in NW Europe and around the Black Sea.

Box 1: Plausible scenario for extreme weather's impacts on crop production

Analysis of the historical records indicated that in 1988/89 there was a significant drought-related impact on the yields of maize and soybean, and in 2002/3 drought impacted on wheat in Europe, Russia, India and China and rice in India. The global production loss estimated from the historical and simulated anomalies using the Global Gridded Crop Model Intercomparison (GGCMI) data for the four crops in 1988/9 and 2002/3 are given in Table 1. Our plausible worst case scenario is that the two patterns of weather - that resulted in maize and soy, and wheat and rice being significantly affected - occur simultaneously. Without further work we cannot quantify the risk of this scenario, but we consider that a significant impact on all four crops of these magnitudes is plausible.

Table 1. Impacts of weather on production of 4 main crops in 1988/9 and 2002/3 (from Annex A)

CROP	CASE STUDY YEAR	% GLOBAL PRODUCTION DECREASE	ABSOLUTE PRODUCTION LOSS (MILLION TONNES)	MODELLED YIELD LOSS FROM GGCMI (%)
MAIZE	1988	12%	55.9	13.5-16.4
SOYBEAN	1988/89	8.5%	8.9	6.0-6.3
WHEAT	2003	6%	36.6	6.4-9.5
RICE	2002/03	4%	21.7	1.9-3.5

3.1 Changing profiles of risks over time: a first analysis

Through the use of climate models coupled to crop models, we can explore the changing risk of major shocks to the food system. To gauge whether we should be concerned about changing risks, we undertook an initial exploration of existing model outputs using the AgMIP/ISI-MIP model ensemble[16]. In terms of global calorie-weighted yields of maize, soy, wheat and rice produced, the ensemble produces a distribution of yields in response to modelled weather (shown in Fig 3 as histograms for "historical" and "near-term" future, and as box plots for 4 time periods). Comparing the histograms, there are changes in the shape of the distribution in future relative to the last decades: they "flatten out". This change in shape represents a significant increase in variance between the modelled historical and the near term future (For Fig 3's top histograms, the near-term future variance increases 43% relative to the historical, Fisher Variance Ratio Test, P<0.0001), and this increasing variability continues to increase throughout the century (Fig 3, top right hand panel).

This ensemble analysis suggests that what we would call an extreme food production shock in the late 20th century will become more common in the future (Fig 3). These data indicate that a 1-in-200 year event for the climate in the late 20th century equates to a loss of approximately 8.5% (Fig 3 top), and over the next decades (2011-2040), a 1-in-200 year event is about 15% larger in magnitude and equivalent to the loss of 9.8% of calorie production. Furthermore, according to the ensemble, an event that we would have called 1-in-100 years over the period 1951-2010 may become as frequent as a 1-in-30 year event before the middle of the century.

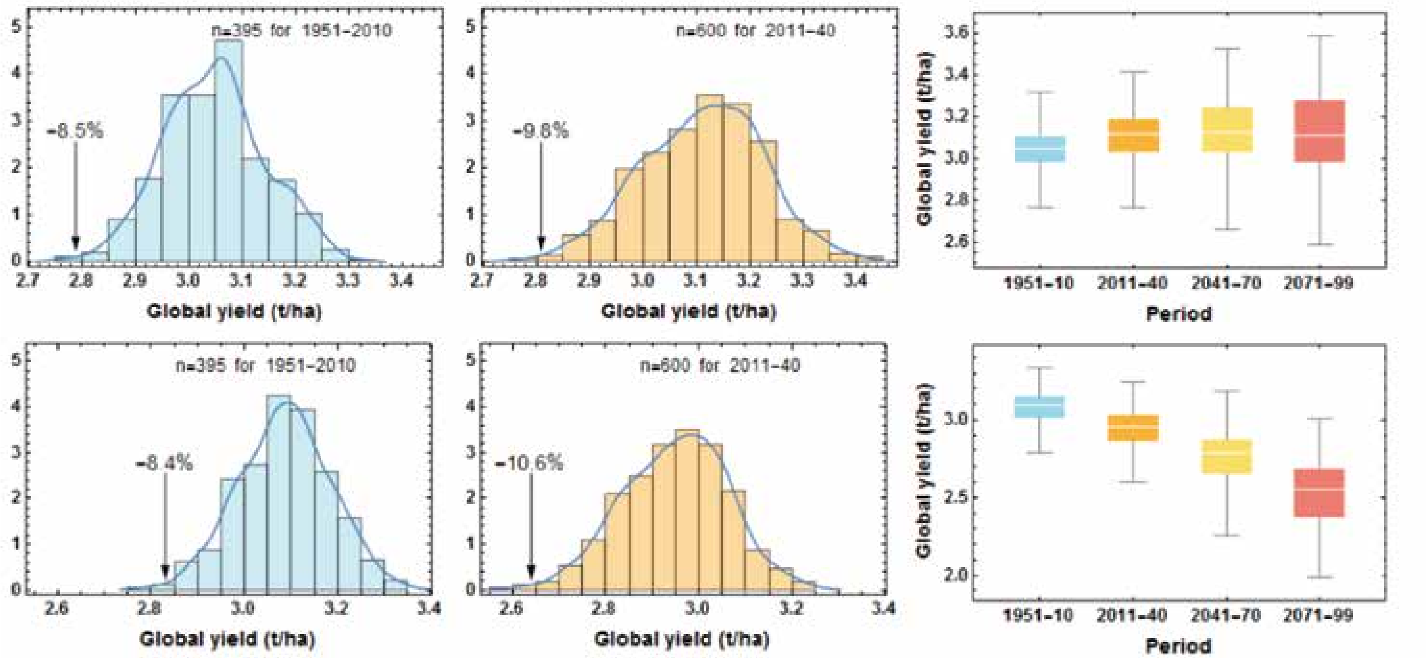

Figure 3: Model-based distributions of global calorie-weighted yield of maize, soy, wheat, and rice for the historical (1951-2010) and near-future (2011-2040) period with (top row) and without (bottom row) the effects of fertilization from increasing atmospheric CO2 included. The estimated magnitude of a 1-in-200 year event in each period is indicated by arrows on the histograms. The box plots summarise the distributions and show the likely increasing variability continuing throughout the century.

The analysis shown in the top row of Fig 3, assumes full effectiveness of CO_2 fertilization. Recently questions have been raised about the magnitude of this beneficial effect[17,18]. If we assume instead that there is no CO_2 fertilization at this large scale, we find similar but even more severe effects in later decades (Fig 3 bottom): a 1-in-200 year event in the near-term future is ~25% greater magnitude and the extreme left tail indicates the potential for historically unprecedented events. Without CO_2 effects, a historically 1-in-100 year event is estimated to occur more than once every 10 years by the second half of the 21st century.

We must emphasise these results are a preliminary analysis and limited by the availability of high-resolution global climate model runs. Significant work is needed to reduce the uncertainty and better understand the way extreme weather may change. Nonetheless, the indications are clear that the global food system is facing increasing risks due to more frequent extreme weather.

4. Policy and market responses to weather-influenced production shocks

Global food trade has increased in recent years, bringing well understood benefits. Trade allows countries with limited productive potential to meet domestic demand; it facilitates specialisation and efficiency; and it generally increases resilience by smoothing local disruptions. However, not all disruptions are equal. As Section 3 highlighted, the system is not robust to a shock in one or more major production regions, pointing to inherent systemic risk in the geographical concentration of global food production.

As noted by May (regarding financial and ecosystem networks, but similarly applies to the global food network which shares some network properties) there is a complex interplay between robustness and vulnerability[19]. Greater interconnectedness reduces countries' vulnerability to local production shocks, but may increase vulnerability to shocks in distant breadbasket regions. It also means the food system is more vulnerable to a sudden reversal in connectivity, for example due to an outbreak of trade restrictions.

A recent study examining the evolution of trade networks over the period 1992-2009 concluded:

> *…the global food system does exhibit characteristics consistent with a fragile one that is vulnerable to self-propagating disruptions. That is, in a setting where countries are increasingly interconnected and more food is traded globally over the [last two decades], a significant majority of countries are either dependent on imports for their staple food supply or would look to imports to meet any supply shortfalls*[20].

In essence, through deeper trade food importing countries have reduced costs and vulnerability to localized production shocks, but at the expense of increased exposure to systemic risks such as a shock in a major production hub or a sudden deterioration in connectivity. Recent price spikes illustrate clearly the systemic risks associated with disruptions in major production regions and/or outbreaks of trade restrictions. Other factors thought to have amplified these price spikes include biofuel mandates, low ratios of stocks relative to demand and depreciation of the US dollar[21].

Historically, following past production shocks, individual grain prices have more than doubled in a short space of time (Annex B). The food system's resilience to a weather-related shock can be defined by how much food prices, access and availability are affected by it. Resilience therefore depends on the magnitude of the physical shock and the policy and market responses that may amplify or buffer its effects as it propagates through the system.

In response to the last decade's food price spikes, many governments have developed strategic responses to better manage food production. However, other key problems pertaining to demand and trade responses remain unaddressed. If we are to avoid the worst impacts of future production shocks, we need to develop greater understanding of how responses may amplify, or mitigate, the price impact of production shocks. These responses are determined by the actions of agents mediated through markets. Governments are significant players in this, both through their direct influence on markets and their indirect influence on the other agents including farmers, food manufacturers and retailers, consumers and relief agencies.

To capture the potential market and government responses to food production shocks in wheat, maize, soybean and rice, we conducted a literature review, undertook a historical data analysis and completed ~50 interviews with experts from industry and policy around the world (Annex B). Taking the plausible worst case production shocks set out in Box 1 as a starting point, we developed a detailed scenario of how weather and responses may interact on a global scale to produce a significant market shock. Below we present this scenario for 2016 and 2026, assuming a plausible deterioration in food system resilience in the latter case.

Economic modelling of the price impacts of these scenarios has not been possible, and in any case, typical economic simulation models are poorly suited to modelling short-run prices during periods where markets are in disequilibrium and the magnitude of the shock is significantly "out-of-sample". Nevertheless, it is our judgement that the combined production shock and responses outlined below in the 2016 plausible worst case scenario could see the FAO food price index reach record highs, surpassing 250 compared to around 170 at the time of writing, with a likely trebling in the price of individual grains. By way of comparison, the index reached 226 in 2008 and 238 in 2011. All other things being equal, the 2026 scenario would be expected to result in an even higher price spike. Economic modelling of these scenarios would be one subject for subsequent research.

4.1 Plausible scenarios[22] for extreme weather and country responses

4.1.1 A plausible worst case scenario for 2016

A disappointing Indian monsoon the previous year means 2016 opens with a poor outlook for wheat in India. But it is not until early spring, when large areas of the Black Sea winter wheat crop are killed by a temporary snow thaw and refreeze, that alarm mounts. Russia and Ukraine both impose export bans in an effort to conserve domestic supply[23]. International wheat prices climb rapidly, precipitating a flurry of similar measures among Kazakhstan, India, China and Pakistan; Argentina tightens existing export restrictions[24]. Several countries including China, Saudi Arabia, Morocco and Iran implement measures to reduce import prices, such as tariff reductions or consumption subsidies[25].

In early spring, the wheat harvest begins in India and the poor outlook is confirmed. Expectations are similarly poor for the Chinese wheat harvest, due to begin later in the season. In response both governments increase export controls on rice in a bid to shore-up domestic availability of cereals. Pakistan and Bangladesh follow suit[26]. As mounting export controls constrain supply, the number of importing countries slashing cereal tariffs or hiking consumption subsidies continues to grow, driving up effective demand.

In late spring, drought sets in in North America and persists throughout the summer. Soybean and maize forecasts drop steadily

over the period whilst prices, already dragged high by wheat, climb rapidly. Argentina raises export taxes on both commodities; China imposes an export tax on maize[27]. The situation is compounded by a heatwave and drought that hits the European wheat crop, leading to further rises across all cereals. The US indicates it will not waive the ethanol mandate despite calls for it to do so, from other governments and from interests in the livestock and food and beverage sectors[28].

In early summer a second failure of the Indian monsoon is confirmed, raising concerns about the rice harvest later in the year. Panic sets in in the rice market, where Asian households, recalling the 2008 crisis, have been steadily hoarding. Myanmar, Sri Lanka, Egypt and Nepal impose export restrictions[29]. Major importers such as Nigeria, Malaysia and the Philippines place orders far in excess of normal levels in a bid to calm domestic markets, bidding-up a tight market. The commitment from governments in the Association of SE Asian Nations (ASEAN) to coordinate trade responses buckles under pressure and Vietnam, Cambodia and Indonesia impose export bans[30].

4.1.2 Plausible scenarios for 2026

Factors that may amplify the impact of production shocks in 2026

The consequences for global food security of any production shock depends not only on the responses of key actors, but critically also on the overall resilience of the food system and prevailing macroeconomic conditions. It is far from difficult to develop a plausible worst case scenario for 2026 in which system resilience is lowered over the next decade and macroeconomic conditions unfavourable, making the global food system considerably more vulnerable to the same shocks.

The following factors would cumulatively reduce the resilience of the global food system to supply shocks and increase the likelihood of a price crisis.

- ***Low stock-to-use ratios.*** *Over the next decade, a number of trends combine to drive down stock-to-use ratios to below crisis thresholds[31] by 2026. At the global level, sluggish yield growth means production struggles to keep pace with demand, driven by increasing consumption of animal products, increasing biofuel use and population growth, generating sustained downward pressure on stocks. Two disappointing global harvests in 2024 and 2025 see stock-to-use ratios fall below 20%.*
- ***Reduced self-sufficiency of China.*** *China has maintained levels of self-sufficiency in cereals in the range of 95-105% since the mid-1990s, reducing its impacts on the international market. However recent years have been characterised by modest but persistent trade deficits, reflecting the growing challenge of meeting increasing demand with a depleted resource base. Over the coming decade, these deficits steadily increase. Soil depletion, pollution and constraints on availability of water and arable land cause production to fall further behind demand. Farms become less competitive with imports due to a high renminbi, aging rural workforce and increasing labour costs. In an effort to contain domestic inflation the government allows imports to rise, increasing demand on international markets.*

- ***Increasingly inelastic demand.*** *By 2026, demand is more inelastic, meaning that a greater price change is needed for demand to adjust. Two factors contribute to this. First, higher incomes in the developing world mean consumers are slower to adjust consumption in response to price increases. Second, and more importantly, further implementation of inflexible biofuel mandates – primarily in developing countries – makes demand more inelastic.*
- ***Recovery of oil prices.*** *A sustained period of international oil prices around $60 a barrel sees investments in production and exploration cut back, leading to a subsequent supply crunch. Prices climb steadily from 2020, and then rise rapidly in 2024 and 2025 due to instability in the Middle East. This feeds through to food prices via a cost push effect, and increases demand for biofuels.*
- ***Cumulative underinvestment in infrastructure in key exporting regions.*** *Three of the most important export regions – Brazil, the USA, and the Black Sea region - face serious infrastructural constraints that are already limiting their export capacity at the margin, contributing to higher export prices and slower supply responses. Underinvestment in all three regions over the next decade sees the situation deteriorate.*
- ***Depreciation of US dollar.*** *In 2025 and 2026, the US dollar depreciates sharply, leading to an appreciation in the prices of dollar-denominated commodities, including agricultural commodities.*

Under this set of preconditions the production shocks considered here would almost certainly result in a more dramatic price response. Consequently, the responses of societies and governments would likely be more extreme. A larger number of countries would probably experience civil unrest. This would raise the stakes for governments, and result in more states intervening. In such a scenario, Thailand – a crucial rice exporter – might limit exports to contain domestic rice prices for example[33]. Reponses might also be more extreme – for example, governments that apply export taxes or quotas in the 2016 scenario might impose outright export bans. In fragile political contexts where household food insecurity is high, civil unrest might spill over into violence or conflict. The Middle East and North Africa region is of particular systemic concern, given its exposure to international price volatility and risk of instability, its vulnerability to import disruption and the potential for interruption of energy exports[34].

Box 2: Factors that may mitigate the impact of production shocks in 2026

Rather than exacerbate a price spike, smart responses can also mitigate one. In aggregate, the following actions could plausibly limit price rises to within normal levels of annual variability:

- *After an emergency meeting of the Rapid Response Forum early in the year, member governments make a joint commitment not to impose any export restrictions on their agricultural sectors.*
- *ASEAN governments follow suit, with a similar announcement on rice.*
- *Governments in major biofuel consuming countries reduce biofuel mandates, increasing availability of grains and oilseeds and dampening prices. This could be implemented politically – for example an agreement brokered through the Rapid Response Forum. Alternatively, a similar effect could be achieved using call options that trigger when a certain price threshold is breached, effectively transforming biofuel mandates into virtual reserves[32].*
- *Low-income consumers in poor or fragile countries are protected from price rises through cash transfers and social protection arrangements, quelling unrest and reducing the incentives for governments to impose export controls.*

5. How would a plausible worst case scenario impact on societies, economies and the environment?

The preceding section set out a plausible worst case scenario in 2016, comprising a weather-related global production shock amplified through the responses of market actors, that could plausibly result in a spike of the FAO food price index to over 250 in 2016. Based on this scenario, it is possible to consider the potential consequences for human populations and national economies. Information on possible country level impacts was collected through an expert interview process. An "Interview Questionnaire" was developed and a panel of experts from academia/research institutions, government and the private sector were interviewed about the likely impacts in Brazil, China, Egypt, Ethiopia, Europe, India, Russia, Saudi Arabia, and the United States. The country selection criteria are provided in Annex C.

This analysis revealed the following broad expectations of how the plausible worst case scenario might unfold at the national and societal level. These are highly consistent with the impacts observed during the 2007/8 and 2010/11 price spikes.

The hardest impacts would be felt by import dependent developing countries, particular in Sub-Saharan Africa. These countries would be expected to experience the most pronounced short-term deteriorations in poverty rates and nutrition security. At the economy level, impacts would likely include inflation, deteriorations in the balance of payments and budgetary pressures arising from higher food subsidies and social transfers.

Other import dependent countries could experience social unrest. In particular, in the wake of the Arab Spring and ongoing instability in the region, the highly import dependent countries of the Middle East and North Africa region could be particularly vulnerable.

Impacts on major economies would be muted. Consumers in large industrialised countries such as the US and EU, where food represents a small share of household expenditures, would be relatively unaffected[36]. The crop sectors of these economies, and other major agricultural producers, would likely benefit from higher prices, though other sectors could suffer. Poor food consumers in China would likely be relatively unaffected due to government intervention to buffer these households from food price inflation through the use of strategic reserves and price controls.

The supply response may have negative consequences in the longer term. In response to the price spike, agricultural output would likely increase through a combination of extensification and intensification. In the short-term, this would increase supply and help stocks to recover, facilitating a decline in food prices. However, if extensification occurred at the expense of high carbon value and/or high biodiversity value land such as forest, this could have long-term environmental costs. Similarly, unsustainable intensification could degrade soils, deplete freshwater supplies and increase greenhouse gas emissions and eutrophication. The risk of unsustainable production responses is likely to be higher in the event of a dramatic price spike, with potential long-term consequences for the resilience of food production.

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6. Key recommendations for increasing resilience to production shocks at global and local levels

We have argued that the risk of a serious weather-related shock to global food production appears to be increasing rapidly due to climate change. Such an event could have serious implications for the stability of global grain markets and human security in vulnerable countries. Below we set out five broad areas where action can begin to be taken in order to address this.

6.1 Better understand the risks

More research is needed to understand and quantify the risks set out in this paper. Our assessment is that they are non-trivial and increasing, but our knowledge of how extreme weather may be connected across the world, and hence the precise probability of multiple bread basket failures, is limited by available model simulations. Modelling limitations also constrain our ability to understand how production shocks translate into short run price impacts. Specific opportunities include:

- High-resolution global climate model runs using stationary present day radiative forcing, with an ensemble size that is sufficient for probabilistic analysis of extreme event risk. Similar stationary forcing runs for snapshots of future forcing would also be needed.
- Development of economic modelling to dynamically capture the transmission of shocks through the trade network, and the impacts of stock levels on price elasticities and different trade responses such as export controls or panic buying on short run prices.
- Development of crop modelling to better incorporate on-going adaptation responses, physiological mechanisms, genetic variation and improvement in response to extreme growing conditions.

6.2 Explore opportunities for coordinated risk management

As knowledge emerges regarding plausible worst case scenarios, it will be possible for governments, international institutions and businesses to develop contingency plans and establish early warning systems with agreed response protocols. Other opportunities include coordinated management of emergency and/or strategic reserves.

6.3 Improve the functioning of international markets

History demonstrates that the actions of market participants in response to production losses, or the behaviours of other actors, are a crucial determinant of price impacts. Other problems that can exacerbate price spikes include low levels of stocks relative to consumption, poor transparency of market information and physical limitations on trade such as infrastructural constraints. Interventions to reduce the risk of extreme price responses include:

- Improving the quality and accessibility of key market data, not least estimates of public and private stockholdings. Building on the recent success of the Agricultural Market Information System will be important in this regard.
- Agreeing international rules to limit the scope for unilateral export controls in the agriculture sector.
- Developing mechanisms to increase the flexibility of biofuel mandates.
- Research to identify critical geographical pinch points in international trade and approaches to address their vulnerability, such as investment in infrastructure or plurilateral agreements to maintain sea lanes for example.

6.4 Bolster national resilience to market shocks

Governments should also consider policies to bolster national resilience to international market shocks. This is a particularly important policy agenda for import dependent developing countries with high numbers of poor food consumers, and/or high risk of political instability. The precise mix of appropriate policy measures will vary according to national context. Options include:

- Investing in strategic storage.
- 'De-risking' imports through, for example, diversification of supply or use of forward contracts.
- Developing methodologies to measure and monitor household vulnerability and using these to design and target interventions such as social protection or safety net programmes.
- Investing in domestic production (its amount and diversity) to reduce dependency on imports.

All are likely to entail cost and many may present significant implementation challenges. It is also noteworthy that, unlike those set out in 6.3, these interventions need not necessarily contribute to overall system resilience. For example, increasing domestic production should improve system resilience at the margin and in the short-term, but may be environmentally unsustainable. If the objective is to use export restrictions to secure output for domestic consumption in the event of a price spike, the consequence for system resilience will be negative. It is important to find ways to strike an appropriate balance among competing objectives, and to identify approaches that minimize negative effects in other policy areas.

6.5 Adapt agriculture for a changing climate

Demand for food, at a global level, is increasing faster than agricultural yields are growing[37]. Agriculture therefore faces a triple challenge. Productivity – at a global level - must be increased by reversing declines in yield growth and closing the gap between actual and attainable yields in the developing world, whilst also reducing its environmental impact. However, given the increasing risk of extreme weather, this cannot come at the expense of production resilience. Increases in productivity, sustainability and resilience to climate change are required. This will require significant investment from the public and private sectors, as well as new cross-sector collaborations between scientists, agriculture, water and environmental specialists, technology providers, policy-makers and civil engineers among others.

EXTREME WEATHER AND RESILIENCE

- Isolated crises have occurred before: for example, in 1988/89 there was a significant drought related impact on the yields of maize and soybean, and in 2002/03 drought impacted wheat in Europe, Russia, India, and China; rice in India.

OPERATING CONTEXT || **2016…** **…by 2026 ?**

- Escalating demand for food
- Trade volume and interdependencies amplify shocks
- Crop production concentrated in global regions, increasing exposure to extreme weather risks
- Reduced self sufficiency in China for cereals
- Increasingly inelastic demand

MULTIPLE BREADBASKET FAILURE

EXTREME WEATHER disrupts production

- Poor Indian monsoon, reduces wheat crop in India and China
- Early Spring thaw-freeze in Black sea area affects wheat crop
- Summer drought in N. America affects maize and wheat forecasts
- Heat wave and drought in Europe affects wheat crop
- Indian monsoon second failure, causes rice harvest concerns

ESCALATING PANIC exacerbates crisis

- As cereal prices climb, export bans are imposed
- Countries impose tariff reductions or consumption subsidies
- China and Argentina raise export taxes on Soybean and Maize
- The US does not waive the ethanol mandate
- Hoarding and further export restrictions in SE Asia
- Further export bans are imposed
- Low stock to use ratio raises concerns of availability

PRICE volatility
EXPORT bans
Import Restrictions

KEY RECOMMENDATIONS ||

- Adapt agriculture to account for climate extremes
- Better understand the risks by improving climate, economic and crop modelling tools
- Better coordinate risk management
- Do not impose export restrictions

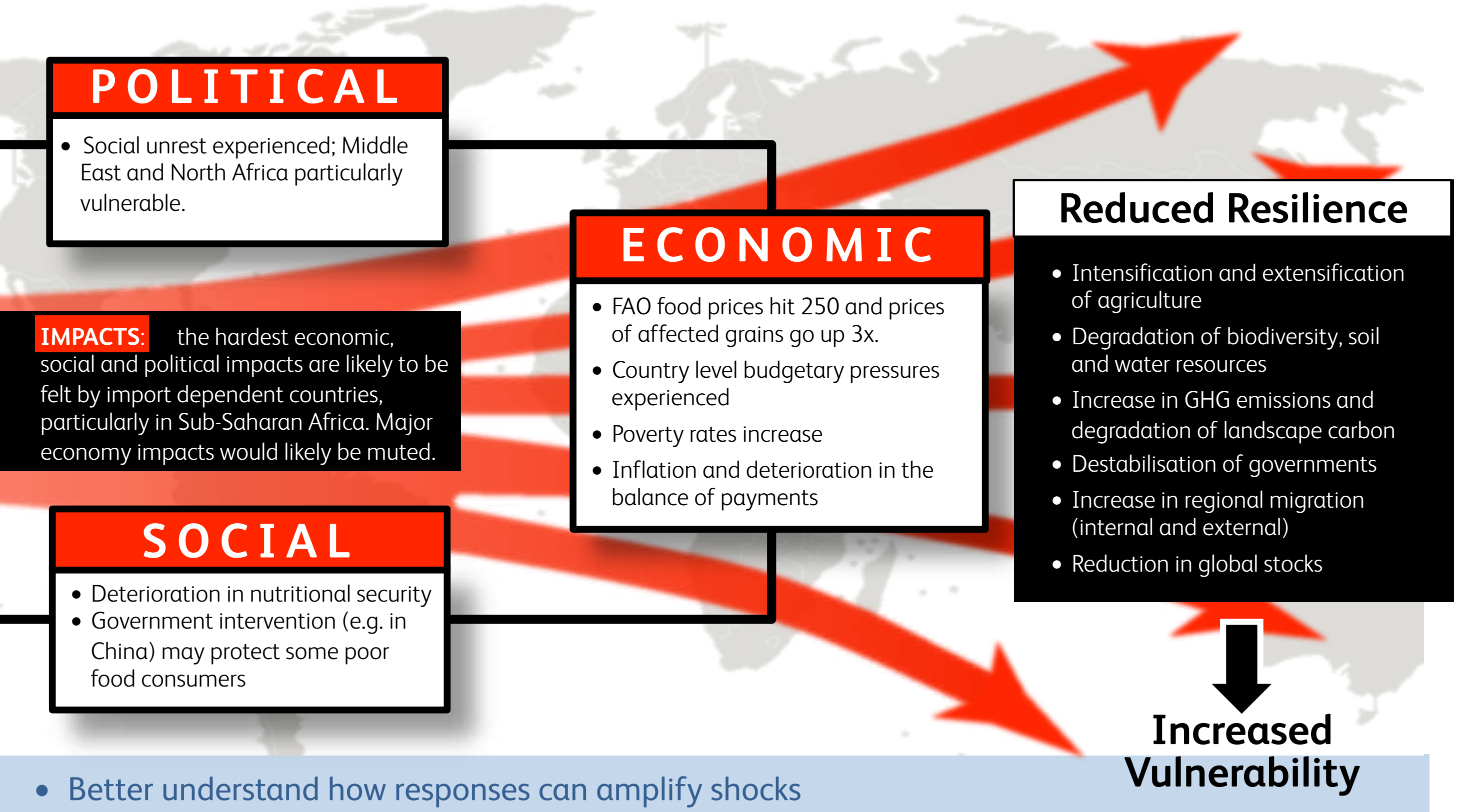
- The above visualisation represents a fictional, but plausible 2016 scenario outlined in the Resilience Taskforce summary report.
- Text in red indicates how the scenario could develop further in a 2026 situation.

Figure 4: A visual summary of the scenarios presented in the report.

OF THE GLOBAL FOOD SYSTEM

- The level of risk is growing: evidence suggests that the risk of a 1-in-100 year production shock event from extreme weather, could increase to 1-in-30 year or more in the next few decades.
- Extremes are where the greatest impacts from climate change will be felt, but predicting the frequency and intensity of extreme events is extremely challenging.

- Key Food import states, economically and politically unstable
- Greater interdependencies
- Production struggles to keep pace with demand
- Underinvestment in exporting region infrastructure
- Recovery of oil prices



- Better understand how responses can amplify shocks
- Improve function of international markets
- Bolster national resilience to market shocks
- Make biofuel mandates more flexible
- Implement mechanisms to protect low income, fragile countries

- The scenario originated from the isolated crises outlined above in 1988/89 and 2002/03, occurring simultaneously.

Appendix

Contributors to report and attendees at workshops in Chicago (C) and London (L)

- John Beghin, Iowa State University (C)
- Judy Buttriss, British Nutrition Foundation (L)
- Riaz Bhunnoo, Global Food Security Programme (C,L)
- Chris Brown, ASDA (L)
- Kris Carlson, Thomson Reuters (C)
- Erik Chavez, Imperial College London (C,L)
- Nancy DeVore, DHF Team LLC (C,L)
- Kenneth Donaldson, Actuary (L)
- Rowan Douglas, Willis Research Network (C,L)
- Gordon Friend, Defra (C,L)
- Olivia Gray, Willis (C)
- Jay Gulledge, Oak Ridge National Laboratory (C,L)
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- George Prpich, Cranfield University (C,L)
- Sherman Robinson, CGIAR (L)
- David Robson, Scottish Government (C,L)
- Simon Sharpe, Foreign and Commonwealth Office (C,L)
- Lucy Stanbrough, Lloyds (L)
- Jack Westwood, British Consulate-General, Chicago (C,L)

**Contributed after the workshops had taken place*

The following have been interviewed to date as part of this work:

- Zhang Hongzhou, Nanyang Technological University, Singapore
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- Nancy DeVore, Bunge Global, USA
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- Jonathan Horrell, Mondelez, Canada
- Gordon Friend, DEFRA, UK
- Corey Cherr, Thomson Reuters, USA
- Chris Brown, ASDA Walmart, UK
- Jerry Hjelle, Monsanto, USA
- Jay Gulledge, Oakridge National Laboratory, USA
- Marc Sadler, World Bank, USA
- Puvan J. Selvanathan, UN Agriculture / Global Compact, USA
- Samir Saran, ORF, India
- Tom Lumpkin, CGIAR, Mexico
- Jerry Skees, University of Kentucky, USA
- Professor Paul Teng, National Institute of Education, Singapore
- Stephen Lorimer, Ministry of Business, Innovation and Employment, New Zealand
- Jonatan Lassa, United Nations University, Singapore
- Dave Gustavsen, ILSI, USA
- James Jones, University of Florida, USA
- Mark Rose Grant, IFPRI, USA
- Don Seville, Sustainable Food Lab, USA
- Chris Joknik, Oxfam, USA
- Gerald Nelson, University of Illinois, USA
- John Antle, Oregan State University, USA
- Erik Chavez, Imperial College, UK
- Margaret Walsh, USDA, USA
- Eija Pehu, World Bank, USA
- Mukul Sanwal, Institute for Defence Studies & Analyses / UMass Amherst, India
- Arunabha Ghosh, CEEW, India
- Naomi Hossain, University of Sussex, Indonesia
- Robin Lougee, IBM, USA
- Biraj Patnaik, Supreme Court Commissioners Office on Right to Food, India
- John Magrath, Oxfam, UK
- Tassew Waldehanna, Addis Ababa University, Ethiopia
- Anne Roulin, Nestle, Switzerland
- Felino Lansigan, Univ. of the Philippines Los Banos, Philippines
- Simon Ticehurst, Oxfam, Brazil
- Elias Fereres, Irrigation Science, Journal, Spain
- Sir Gordon Conway, Imperial College, UK
- Joanna Syroka, WFP, USA
- JohnIngram, Oxford University, UK

- Bruce Babcock, Iowa State University, USA
- Helen Edmundsen, DfID, UK
- Renato Maluf, Rural Federal University of Rio de Janeiro, Brazil
- Claudia Schmitt, Rural Federal University of Rio de Janeiro, Brazil
- Zhang Hongzhou, Nanyang Technological University, Singapore
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- Tarek Tawfik, ENCC Food Security and Safety Sub-Council, Egypt
- Amina Ghanem, Egyptian National Competitiveness Council, Egypt
- James McCann, Boston University, USA
- Bart Minten, International Food Policy Research Institute (IFPRI), Ethiopia
- Chris Brown, ASDA/Walmart, USA
- Biraj Patnaik, Supreme Court Commissioners Office on Right to Food, India
- Yury Safonov, Moscow Higher School of Economics, Russia
- Blair Fortner, Monsanto Company, USA

A workshop hosted by Chatham House on February 11th 2015 refined the Responses report. Those attending the workshop were:

- Nick Silver, Institute of Actuaries
- Paul McMahon, Associate Fellow, Chatham House / Managing Director, SLM Partners LLP
- Gordon Friend, DEFRA
- Maria Lacunza, DEFRA
- James Ballantyne, FCO
- Rowan Douglas, Willis Research
- Olivia Gray, Willis Research
- Laura Wellesley, Chatham House

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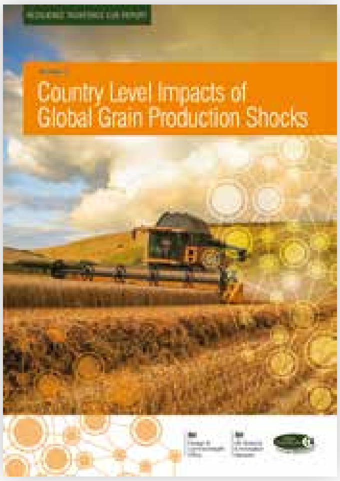

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